Four-Wheel Steering

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ABSTRACT:

This prototype Four-Wheel Steering system is designed for a Formula SAE racecar. Multiple steering geometries can be applied to optimize the handling across a range of speeds. Ackermann steering geometry at low speeds improves the car's agility in tight, technical race courses. At high speeds the steering transitions to parallel steering geometry, improving stability and giving the driver more precise control over the vehicle. The system fits seamlessly within the rear suspension packaging of the existing WashU Racing vehicle design and minimizes addition of weight by using compact and lightweight electronic linear actuators to steer the rear wheels. In testing of the system on the WashU Racing racecar, a successful prototype was rendered. It was found in order to eliminate error in the actuator movement, a more developed control system is needed to be designed. Testing of the turning radii for standard steering, low speed Ackerman, and high speed in-concert steering yielded successful results. For a left-handed turn, standard steering resulted in a 20' radius, the low speed Ackerman resulted in a 15' radius, and the high speed in-concert resulted in a 24' radius. Overall, the successful prototype gives hope for the system to be fully implemented within the next couple of years. Full testing of the system can be completed once a safer, and more accurate control system is implemented.

MEMS 411 Group I

Four-Wheel Steering

Andrew Sparrow, Phil Rowsell and Theo Wisniewski

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1 INTRODUCTION

1.1 PROJECT PROBLEM STATEMENT

Formula SAE is a student design competition sponsored by the Society of Automotive Engineers. Teams design, build, and compete with a small open wheel racecar in an international competition among engineering schools. The racecars are evaluated on their dynamic performance, design process and solutions, and business concerns such as cost and marketability. In this highly competitive field teams must build an extremely agile and lightweight vehicle to succeed in the competition's tight autocross courses. Four-wheel steering is an advanced method of improving a car's handling capabilities and adding additional parameters for tuning the car's dynamic profile. The problem is to design a four-wheel steering system to go on the WashU Racing FSAE racecar.

1.2 LIST OF TEAM MEMBERS

Andrew Sparrow, Phil Rowsell, and Theodore Wisniewski.

2 BACKGROUND INFORMATION STUDY – CONCEPT OF OPERATIONS

2.1 A SHORT DESIGN BRIEF DESCRIPTION THAT DESCRIBES THE PROBLEM

The WashU Racing team desires to improve its standing in the FSAE competition. The team took in 39th place in 2015 and 74th place in 2016 and is looking for design changes that will improve its standing in future competitions. We propose the design of a Four-Wheel Steering System (4WS) to improve the stability and performance of their FSAE vehicle. The 4WS system must be lightweight and meet competition rules for safety and performance.

2.2 SUMMARY OF RELEVANT BACKGROUND INFORMATION

Porsche implements the function of rear wheel steering on their line of sport cars such as the Porsche 911 GT3 RS. Porsche uses an electromechanical adjustment system, shown in Figure 1, at each wheel to improve handling and agility. The system is dependent on the steering input and vehicle speed.

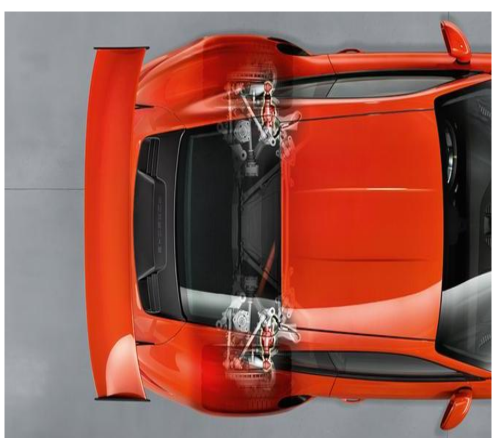

Figure 1 Image of the 4WS system on a Porsche 911 GT3 RS. The linear actuators are highlighted in red.[1]

[1] "Rear-axle steering," Porsche, http://www.porsche.com/uk/models/911/911-gt3-rs/chassis/rear-axle-steering/

Honda was one of the first to successfully incorporate 4 Wheel-Steering onto an automobile in the late 80's. The 1988 Honda Prelude was the first active 4WS car to hit the market. The vehicle used a mechanical gearbox in the rear, shown in Figure 2, with an axle that ran the length of the car to coordinate the front and rear steering efforts, shown in Figure 3. 4WS for commercial automobiles proved to be expensive and not essential to the consumer's needs.

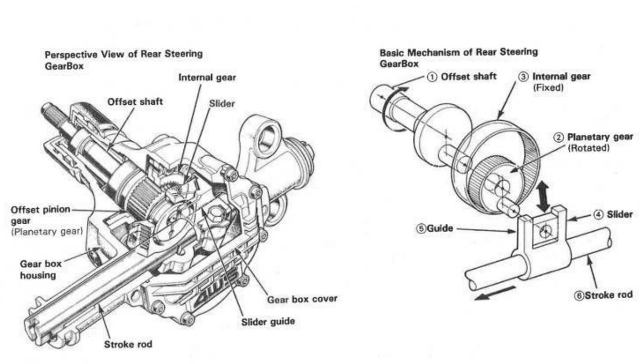

Figure 2 Internal view of the rear steering box for the Honda Prelude which allowed it to achieve active steering.[2]

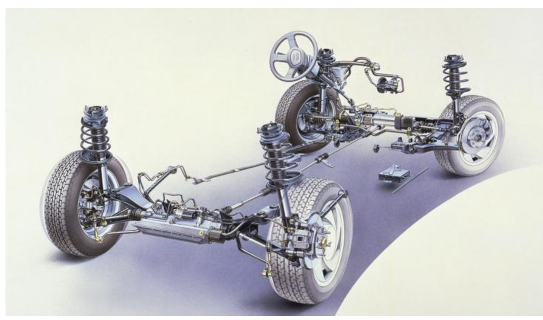

Figure 3 A view of the 4WS system of the Honda Prelude without the chassis.[2]

The biggest risk involved with 4WS is the concern of the rear system was to fail or lose power since they will not have a direct mechanical connection to the front like the Prelude. If the rear wheels remain locked-up in a potentially dangerous position it will put the driver at high risk. A Fail-Safe system is needed to ensure driver safety.

Relevant Codes/Standards:

There are specific rules pertaining to 4 wheel-steering in the FSAE competition rule book that must be followed accordingly to keep the car legal for racing. Also since an electrical system is to be implemented for the 4 wheel-steering design, it seems relevant to follow standards pertaining to electrical equipment installed in passenger vehicles. The standard to be followed is **ISO 26262 - Functional**

[2] "Four-wheel steering demystified," Autoweek, http://autoweek.com/article/car-life/four-wheel-steering-demystified

Safety of electrical or electronic systems in passenger cars. However, due to the price of this standard we were unable to purchase it.

Design Brief:

The WashU Racing team desires to improve its standing in the FSAE competition. The team took in 39th place in 2015 and 74th place in 2016 and is looking for design changes that will improve its standing in future competitions. We propose the design of a Four-Wheel Steering System (4WS) to improve the stability and performance of their FSAE vehicle. The system will be composed of the standard rack and pinion steering in the front, but will have an electronic sensor that notifies 2 linear actuators in the rear to turn the wheels accordingly depending on the speed of the vehicle. The 4WS system must be able to turn the rear wheels in both direction depending on the speed of the vehicle. At high speeds, the rear wheels will turn in the same direction as the front wheels to allow for stability through high speed turns. At low speeds, the rear wheels will turn in the opposite direction as the front wheels to allow for a sharper turning radius. This function increases the laterally agility of the vehicle and can be a significant increase in performance for FSAE competition.

The linear actuators must be able to run on a 12 V battery and pull low currents around 3 to 5 amps or less. They must also be able to extend and retract over a range of approximately 2 to 4 inches and have fast enough travel speeds to prevent lagging between the front and rear wheels. A Fail-Safe system must be implemented to return the rear wheels to equilibrium if the system is to lose power or not function properly in order to maintain driver safety.

3 CONCEPT DESIGN AND SPECIFICATION – DESIGN REQUIREMENTS

3.1 OPERATIONAL REQUIREMENTS ALLOCATED AND DECOMPOSED TO DESIGN REQUIREMENTS

3.1.1 Record of user needs interview

The following are responses from interviews with two customer bases. The first was an interview with Michael Yu the Treasurer for WashU racing. He is a stakeholder as a member of the race team and is also responsible for approving funding within the team for special projects. The second interview was with Dr. Malast and Dr. Jakeila professors for MEMS 411. They are stakeholders in the project because of the funding that they provide through the class. The interviews are presented as the question asked, a summary of their response, the interpreted operational or design requirement, and the level of importance rated from one to five. Five is considered a very important requirement and one is considered a requirement of low importance.

3.1.1.1 Interview with WashU Racing Treasurer – Michael Yu

How does the driver expect the car's feel to change with the addition of four-wheel Steering?

- The driver should be able to expect the turns to be tighter, rotating around the driver rather than the rear following the front. They should also expect to keep more power through turns or expect better acceleration through turns. Also, the system should not have a drastic effect on the feel of the vehicle except for tighter turns.
- Operational Requirement: Active Steering
- Level of Importance: 5

What is your cost expectation for implimenting the four-wheel steering on the racecar?

- The cost including electronics, linear actuators, testing and validation should be expected to cost $2500. In terms of the cost report it whould be between $300 and $600.
- Operational Requirement: Minimal Impact to Cost Report Score
- Level of Importance: 3

What are your safety concerns from a four-wheel steering system?

- The primary concerns are linear actuator failure and the battery overheating. Two wheels free-lancing in the rear and the driver quickly loses the ablity to drive the car. The battery overheating is just dangerous. The advantages of the system are that it makes it safer in turns while working properly because it increases traction.
- Operational Requirement: Safe During Operation
- Level of Importance: 4

What additional weight would be acceptable to be put on the car?

- The max weight that we would want to add with this system would be about 10lbs.
- Operational Requirement: Minimal Added Weight
- Level of Importance: 3

What do you think the Formula SAE design judges would be most concerned about with four-wheel steering?

- They will express similar safety concerns if not addressed. They will also be concerned about whether or not the team understands the theory behind the system. Also considering what event the system is designed for.
- Operational Requirement: Intentional Geometry
- Level of Importance: 4

Figure 4 Interview with final product stakeholder, 2016-17 Treasurer of the WashU Racing FSAE team.

3.1.1.2 Interview with MEMS 411 Professors – Dr. Mark Jakiela and Dr. Mary Malast

What do you expect from our working prototype?

- A subset of hardware that demonstrates the overall concept of the project.
- Operational Requirement: Active Steering
- Level of Importance: 5

What is your cost expectation for building the working prototype?

- Expect the budget to be anywhere between $300-$400
- Operational Requirement: Low Cost Prototype
- Level of Importance: 5

What are your safety concerns from a four-wheel steering system?

- Proper static analysis of components in CAD software; Meets safety requirements for ASME and FSAE; Does not alter the totality of the car; Electrical safety
- Operational Requirement: Safe During Operation
- Level of Importance: 5

What compromises would you accept from a working prototype compared to a final product?

- Do not need complete assembled car, just needs to demonstrate the key concept of fiinal product
- Design Requirement: Stationary Prototype
- Level of Importance: 5

Figure 5 Interview with prototype stakeholders, Dr. Mary Malast and Dr. Mark Jakiela.

3.1.2 List of identified operational and design requirements

The hierarchy of operational requirements that were taken from customer interviews and background research are shown in Figure 6. The requirements were organized into five main requirements: active steering, electronic control, safe during operation, operating environment, and does not reduce performance. All other requirements were considered sub-requirements.

Figure 6 **Operational Requirements for a four-wheel steering system. The four primary operation requirements are that the steering must be active steering, utilize electronic control, be safe for the driver, and withstand operating conditions.**

The design requirements, shown in Figure 7, were derived from the operational requirements. Each number of an operational sub-requirements were made into specific design requirements.

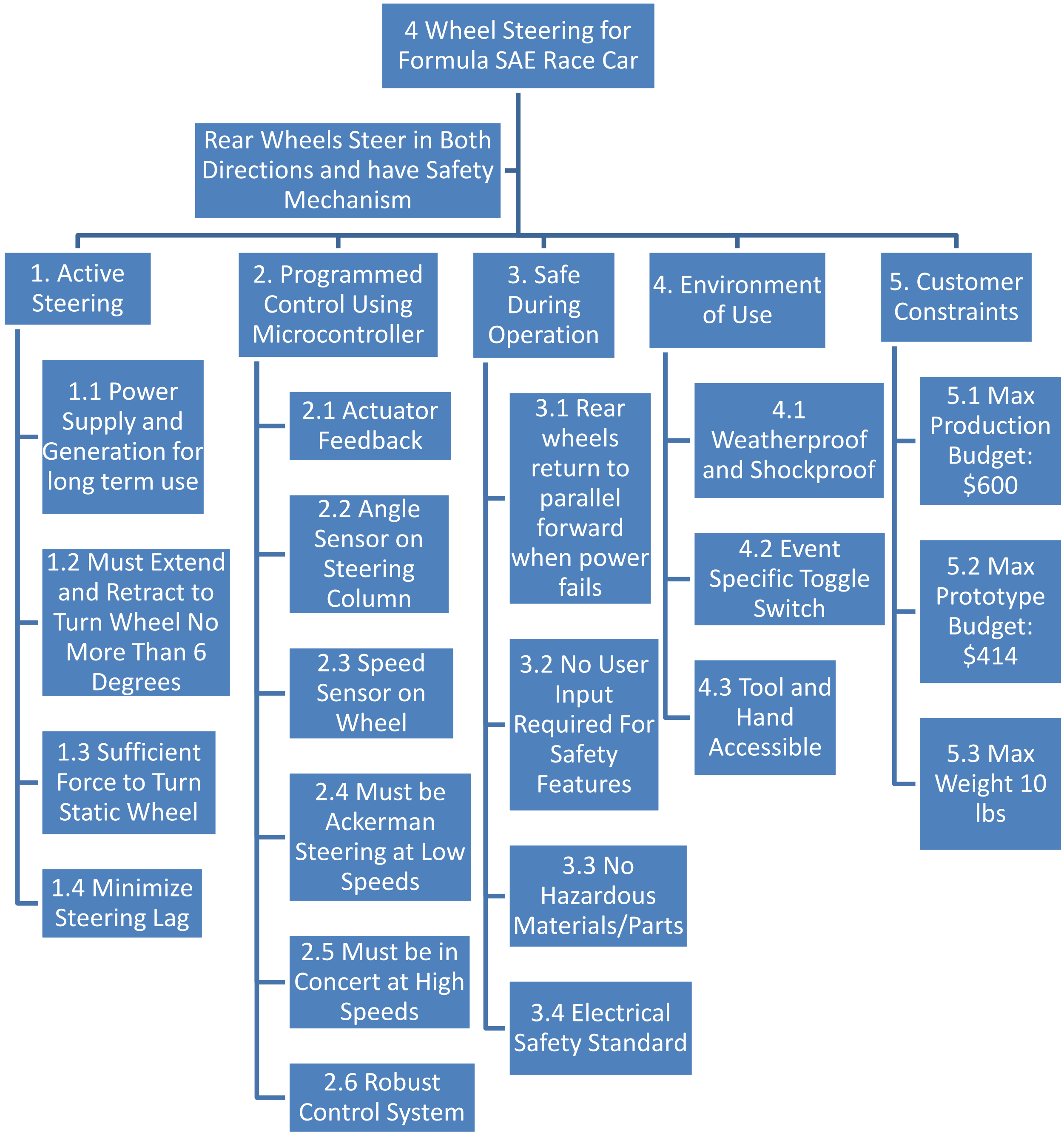

Figure 7 **Design Requirements for a four-wheel steering system. The four primary Design Requirements are that the steering must be active steering, utilize electronic control, be safe for the driver, and withstand operating conditions.**

3.1.3 Functional allocation and decomposition

Functional allocation of these design requirements is discussed on the four concept drawings in section 3.2 below.

3.2 FOUR CONCEPT DRAWINGS

Concept 1 is using hydraulic linear actuators, shown in Figure 8. Concept 2 utilizes electronic linear actuators and replaces the toe links with tie rods, shown in Figure 9. Concept 3 is similar to concept 2, uses linear actuators, except it removes the need to tie rods, shown in Figure 10. Concept 4 uses a single electronic motor that drives a rack and pinion in the rear, shown in Figure 11.

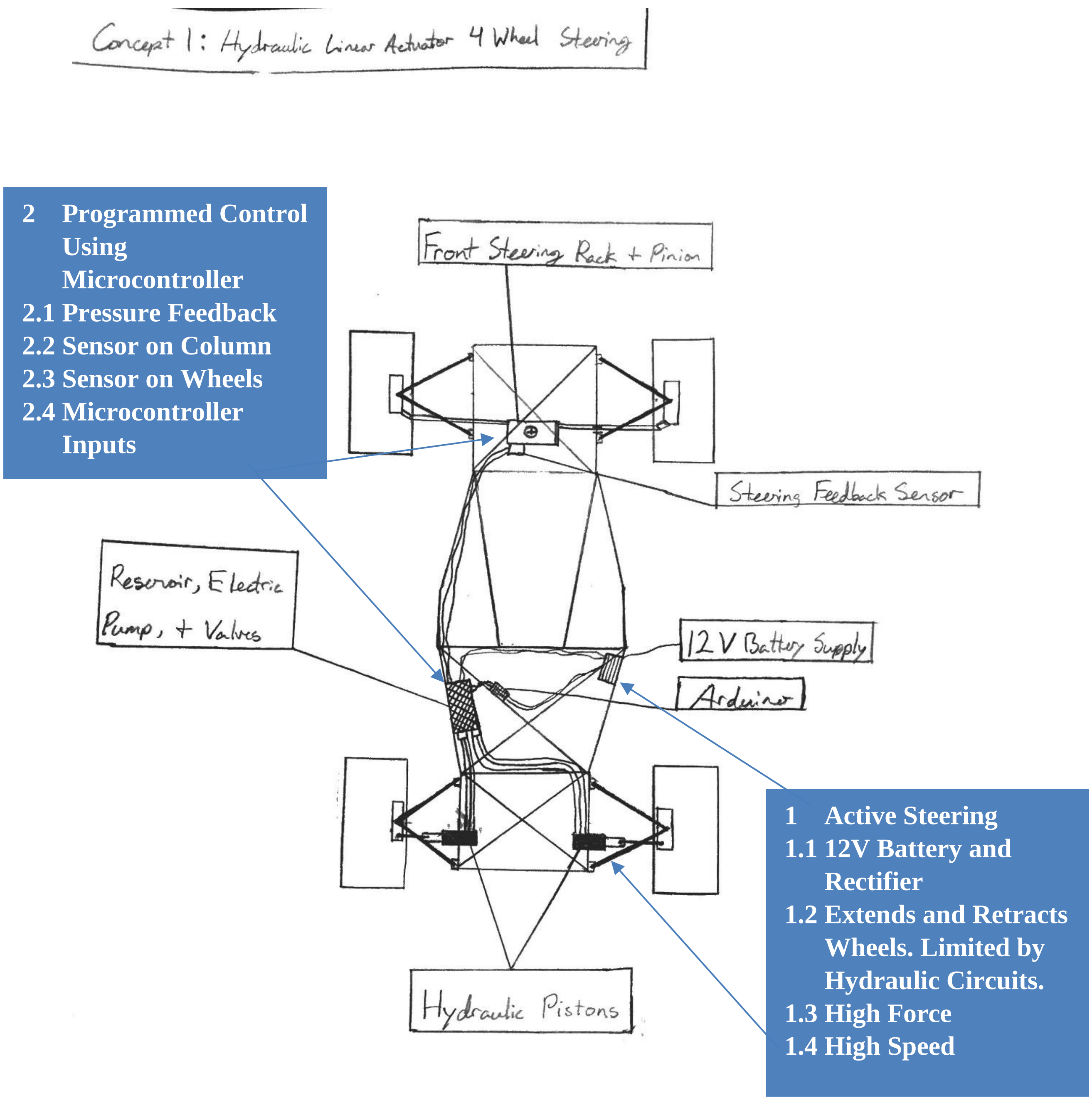

Figure 8 Drawing of Design Concept 1 which is for an electro-hydraulic system. A hydraulic system controlled by a microcontroller would individually change the toe of each rear wheel.

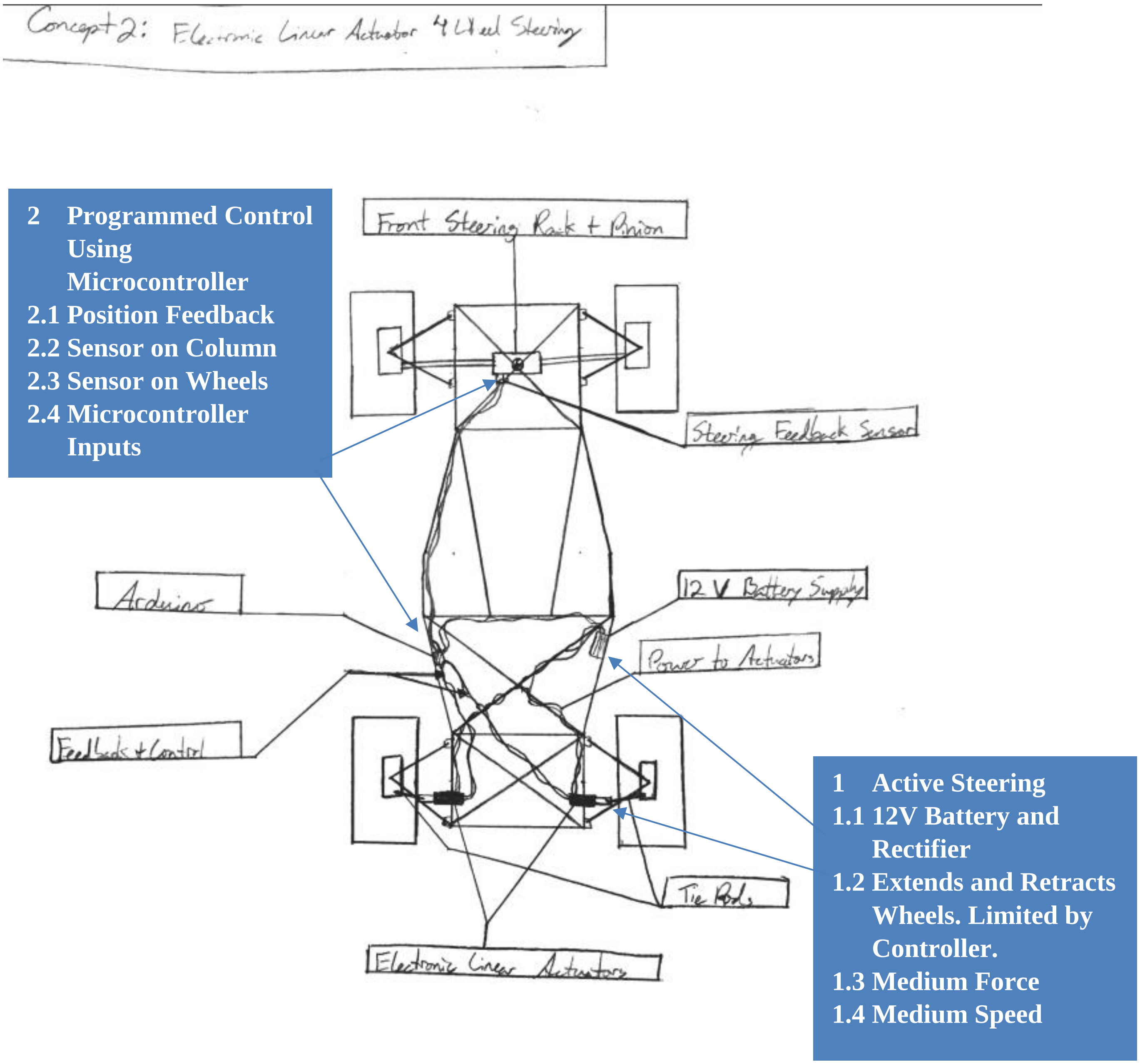

Figure 9 **Drawing of Design Concept 2 which is for an electrical linear actuator system. An electrical linear actuator system, mounted rigidly to the frame, controlled by a microcontroller which would individually change the toe of each rear wheel through a tie-rod.**

Concept 3: Linear Actuators Without Tie-Rods

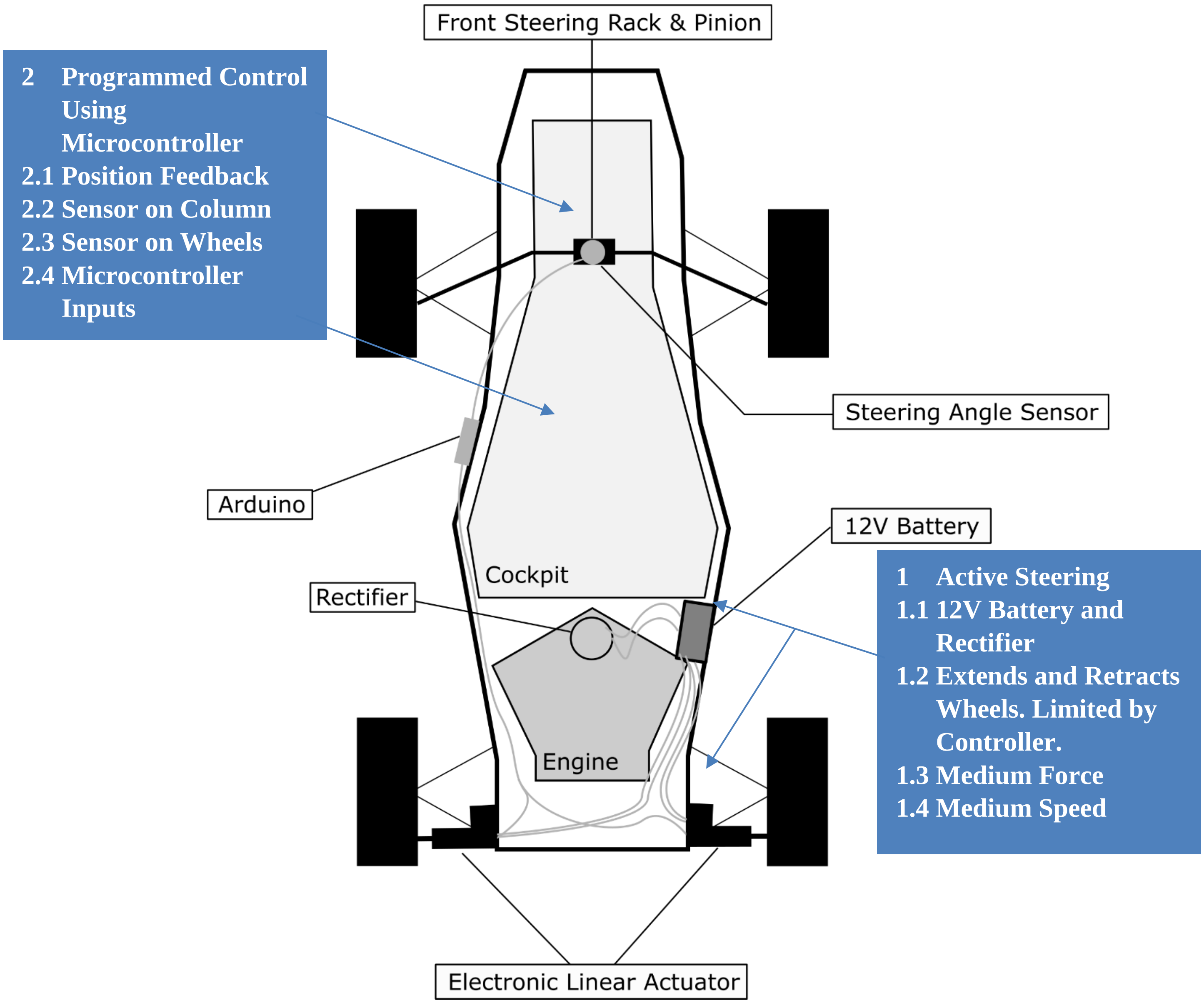

Figure 10 **Drawing of Design Concept 3 which is for an electrical linear actuator system. An electrical linear actuator system, floating between the frame and the upright, controlled by a microcontroller which would individually change the toe of each rear wheel.**

Concept 4: Electric Motor Powered Steering Rack

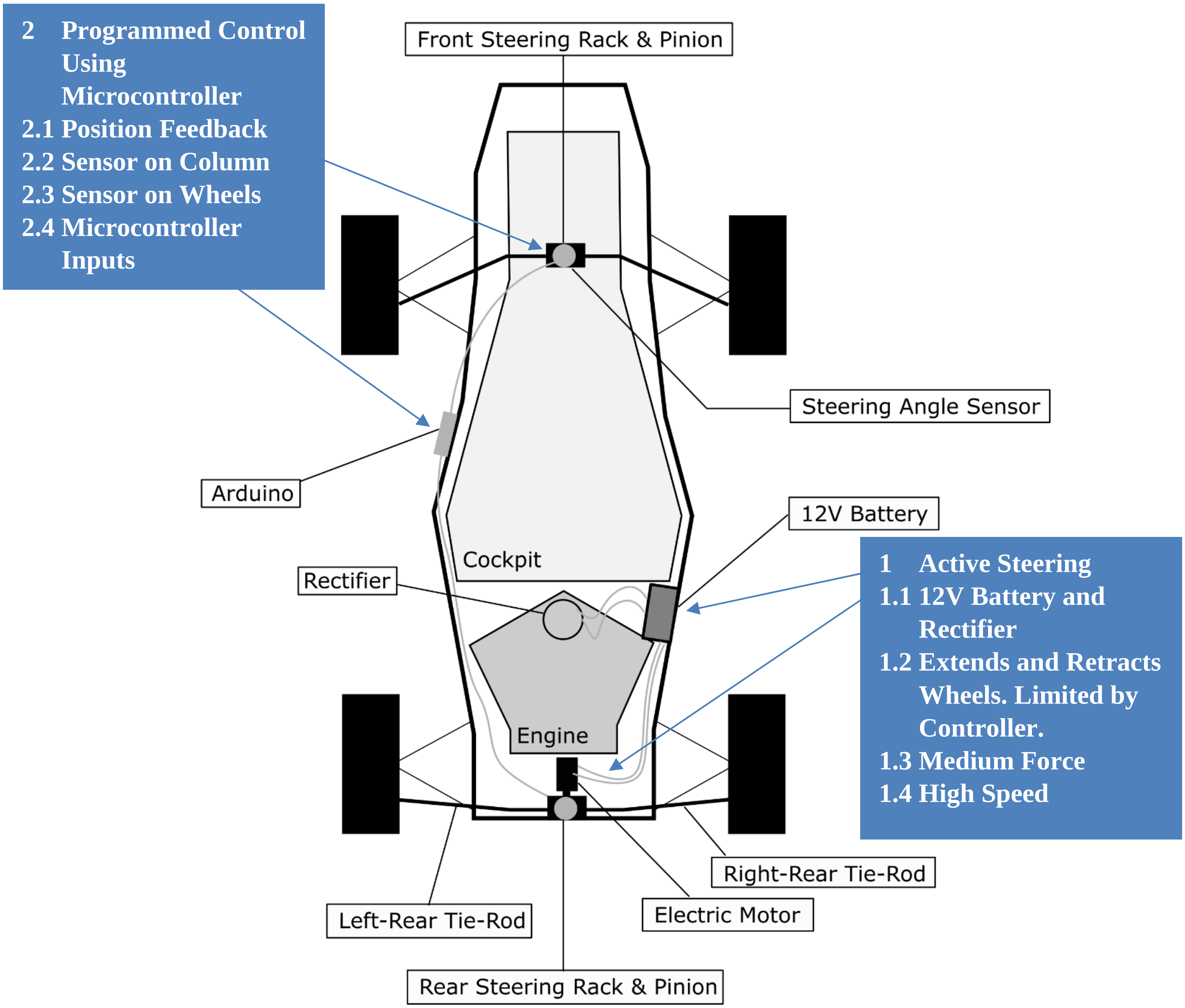

Figure 11 Drawing of Design Concept 4 which is for a single electrical motor with a rack and pinion. The electric motor turns the pinion which turns the wheels. Active steering is achieved by turning both wheels with a single motor.

3.3 CONCEPT SELECTION PROCESS

3.3.1 Preliminary analysis of each concept's physical feasibility based on design requirements, function allocation, and functional decomposition

3.3.1.1 Hydraulic Actuator Concept

This system is composed of two hydraulic cylinders, a fluid reservoir, pump, control system with actuating valves, and hoses. Like the other steering layouts, this would use an Arduino controlled system. The 12V battery supply powers the hydraulic pump in this arrangement. The actuators push or pull on the uprights of the race car in order to steer the wheel in accordance with the front steering. This set-up uses no tie-rods so the actuators are sized such that they connect directly onto the frame and the other end to the upright. The Arduino uses a steering angle sensor as the input of the front steering to produce an output steering angle on the rear wheels. This program will also be a function of speed of the race car.

This system would function ok in the car but be physically awful as an overall system. The hydraulic cylinders can exert forces way greater than what is necessary to turn the wheels and will have to have to be mounted specifically such that the orientation between the frame, upright, and cylinder is appropriate. The worst factor is that the hydraulic system including the fluid reservoir would add up to 50lb to the car which does more harm than good to the performance of the race car. One of the main Design Requirements was to not add more than 10lb to the overall weight of the car so the system is not to slow down the car enough that the 4-wheel steering becomes irrelevant. These considerations were quantified in Table 1.

3.3.1.2 Electronic Linear Actuators with Tie-Rods Concept

This arrangement uses two Firgelli Automation Feedback Rod Linear Actuators combined with an Arduino for control and is powered by a 12V DC battery. The actuators push or pull on the uprights of the race car in order to steer the wheel in accordance with the front steering. This set-up uses tie-rods so the actuators will have to be specially mounted to the frame and the other end to a tie-rod that is connected to the upright. This introduces more weight to the system and different packaging in the rear of the race car. The Arduino uses a steering angle sensor as the input of the front steering to produce an output steering angle on the rear wheels. This program will also be a function of speed of the race car.

This system works well with the race car and is much lighter than the hydraulic and rear steering rack concepts. Having the tie-rods may provide an easier connection to the uprights, but may introduce complications in packaging of the rear of the car. A special mount will have to be created and attached to the frame in order to have the actuator sit the proper distance to extend and retract while turning the wheel. This extra linkage will create some extra factors into the programming of the Arduino in turning the wheel specific degrees in accordance to the front steering. The actuators run about $140 a piece and can exert a force of 150lb at a speed of .5in/sec which is sufficient for turning the wheel in no excess of 6 degrees of steering. The feedback provides exact location of the actuator arm so the Arduino knows its location at all times. These considerations were quantified in Table 2.

3.3.1.3 Electronic Linear Actuators without Tie-Rods Concept

This arrangement uses two Firgelli Automation Feedback Rod Linear Actuators combined with an Arduino for control and is powered by a 12V DC battery. The actuators push or pull on the uprights of the race car in order to steer the wheel in accordance with the front steering. This set-up uses no tie-rods so the actuators are sized such that they connect directly onto the toe-link of the frame and the other end to the upright. The Arduino uses a steering angle sensor as the input of the front steering to produce an output steering angle on the rear wheels. This program will also be a function of speed of the race car.

This system works exceptionally well with the race car and is much lighter than the hydraulic and rear steering rack concepts and slightly lighter than the previous due to no need for tie-rods. Having no tie-rods means less weight added to the system and the linear actuators can have a solid direct connection between the frame and the upright. This also simplifies the travel analysis and turning of the wheel because there is not an extra linkage to account for; the travel of the actuator can be directly applied into the programing without taking into consideration the extra play and distance of an additional tie-rod linkage. The actuator can exert a force of 150lb at a speed of .5in/sec which is sufficient for turning the wheel in no excess of 6 degrees of steering. The actuators run about $140 a piece and can exert a force of 150lb at a speed of .5in/sec which is sufficient for turning the wheel in no excess of 6 degrees of steering. The feedback provides exact location of the actuator arm so the Arduino knows its location at all times. These considerations were quantified in Table 3.

3.3.1.4 Electronic Rear Steering Rack Concept

This arrangement uses a Stiletto 6.4:1 ratio rack and pinion powered by a DC electric motor (Anaheim Automation model # BDBSG-66-187-90V-1800-R49). The steering rack pushes tie-rods to rotate the rear wheels. As with the other concepts, this arrangement requires an Arduino controller, front steering angle sensor, 12V battery power supply, and wiring. The steering rack layout fulfills the functional requirement of controlling the rear wheels independently from the front wheels, so it can follow Ackermann steering geometry at low speeds and turn the rack in the opposite direction at higher speeds to turn the rear wheels in concert with the front wheels. However, the steering rack turns both rear wheels when the pinion gear moves the steering rack, meaning each rear wheel cannot be independently turned.

For speed of steering this layout would be very competitive. The electric motor is capable of turning at 37rpm with an output of 74lb.ft., which would make for a tie-rod speed of approximately 5in/second. The system weight of this layout is less competitive, at about 12lbs. That weight also exceeds the customer's requested maximum weight. The estimated cost for an electric steering rack layout would be about $550. Packaging is also a disadvantage of the steering rack layout. The steering rack needs to be mounted inside the frame and tie-rods must be routed through the same area as the suspension arms, which is more challenging than actuators mounted outside the frame and may require redesign. Feedback can be integrated into the motor at additional cost, so steering rack displacement is known. The feedback is less reliable for the motor though, because its sensor only reads relative displacement rather than position. These considerations were quantified in Table 4.

3.3.2 Concept scoring

Each of the four concepts were scored using a series of metrics including speed of movement, weight, cost, packaging, amount of redesign, and system feedback. Speed refers to how quickly the option moves the steering wheel in inches per second. Weight looks at the projected weight of the system in terms of pounds where heavier is considered worse. Options are also rated on what the project would cost. Packaging refers to how well does the system fit within size and positioning constraints in the vehicle which is subjectively rated on a scale of one to ten. Amount of redesign and system feedback are similarly rated. Individual scores and a normalized value of concept 1 is presented in Table 1, concept 2 is presented in Table 2, concept 3 is presented in Table 3, and concept 4 is presented in Table 4. The normalized values of each metric are combined for a total score. The weighting of each metric is equal.

Table 1 Design metrics and rating for design concept 1, the hydraulic system.

Metric Number	Metric	Units	Worst Value	Max Value	Actual Value	Normalized Value
1	Speed	in/sec	0	5	1	0.20
2	Weight	lb.	45	0	45	0.0
3	Cost	$	600	0	600	0.0
4	Packaging	Integer	10	0	8	0.20
5	Amount of Redesign	Integer	10	0	7	0.30
6	System Feedback	Integer	10	0	8	0.20
					TOTAL	**0.900**

Table 2 Design metrics and rating for design concept 2, electrical actuators with tie-rods.

Metric Number	Metric	Units	Worst Value	Max Value	Actual Value	Normalized Value
1	Speed	in/sec	0	5	0.5	0.10
2	Weight	lb.	45	0	6	0.87
3	Cost	$	600	0	345	0.42
4	Packaging	Integer	10	0	1	0.90
5	Amount of Redesign	Integer	10	0	2	0.80
6	System Feedback	Integer	10	0	1	0.90
					TOTAL	**3.992**

Table 3 Design metrics and rating for design concept 3, electrical actuators without tie-rods.

Metric Number	Metric	Units	Worst Value	Max Value	Actual Value	Normalized Value
1	Speed	in/sec	0	5	0.5	0.1
2	Weight	lb.	45	0	5.5	0.88
3	Cost	$	600	0	325	0.46
4	Packaging	Integer	10	0	1	0.90
5	Amount of Redesign	Integer	10	0	1	0.90
6	System Feedback	Integer	10	0	1	0.90
					TOTAL	**4.136**

Table 4 Design metrics and rating for design concept 4, electric motor with a rack and pinion.

Metric Number	Metric	Units	Worst Value	Max Value	Actual Value	Normalized Value
1	Speed	in/sec	0	5	5	1.00
2	Weight	lb.	45	0	12	0.73
3	Cost	$	600	0	550	0.08
4	Packaging	Integer	10	0	10	0.0
5	Amount of Redesign	Integer	10	0	10	0.0
6	System Feedback	Integer	10	0	3	0.70
					TOTAL	**2.517**

3.3.3 Design requirements for selected concept

3.3.4 Final summary

Our four design concepts for a rear wheel steering mechanism are the following: Electronic linear actuators with tie-rods, electronic linear actuators without tie-rods, electric steering rack, and hydraulic actuators. Analysis using our Design Metrics concluded **electronic linear actuators without tie-rods are the best method of steering the rear wheels**. The primary factors that differentiate the four arrangements are speed of steering, cost, weight, packaging constraints, amount of redesigning required to integrate the system, and feedback to the control system. These factors were chosen based on the functional requirements and Design Requirements. A steering actuator movement of .5in/second for the rear wheels to keep up with the front wheel movement allows the car to respond predictably. The cost analysis excludes the cost of the power supply, Arduino control system, front steering angle sensor, and wiring, because all four layouts would use the same components and they are not a factor in the differential cost analysis. For weight, our goal is to minimize weight as much as possible, but the target is 10lbs added based on feedback from the customer at WashU Racing. Packaging constraints and redesigning are subjective design metrics, but are vital to the success of the project, because the cost and feasibility are dependent on being able to reuse existing components for the prototype system. Finally, the feedback to the control system is needed for safe operation of the car because the Arduino needs to know the wheels' position at all times to accurately control the steering. In the event of system failure, where it produces unexpected performance, there should be a method for the driver to turn the system off locking it in a safe position.

The two electronic linear actuator layouts scored highest on the design metrics, with a Normalized score of 3.992/6.0 for the layout that includes tie-rods and 4.136/6.0 for the layout without tie-rods, as shown in **Error! Reference source not found.**. The primary advantage of the layout without tie-rods is lower weight and a small cost savings due to eliminating a component from each side of the steering system. Both options have packaging tradeoffs. The tie-rods allow more flexibility in selection of linear actuators, but would likely take up more space and introduce an additional failure point. Eliminating tie-rods requires using linear actuators the same length as the toe-links they will replace in the rear suspension, but makes it easier to use the existing attachment points. Both options end up with the same packaging score, but needing to design new attachment points for the linear actuators earn the tie-rod layout a lower score for redesign. These were closely matched, but eliminating tie-rods has a narrow advantage and is our chosen layout.

Table 5 Normalized scoring of the four concept options.

Type of System	Metric Score
Electronic Actuators with Tie-rods	**3.992**
Electronic Actuators without Tie-rods	**4.136**
Hydraulic	**0.900**
Electric with Rear Steering Rack	**2.517**

Both linear actuator layouts compare favorably to the electric steering rack option. The linear actuators proved superior in every metric except speed of steering. The speed of steering provided by the electric motor mounted to the rack and pinion would allow for extremely responsive handling, but exceeds the rate of steering a driver is physically capable of inputting. For weight, the steering rack is twice as heavy as the linear actuators and exceeds the customer's stated maximum weight. This is important because the added weight offsets the handling improvement provided by four-wheel steering. Packaging and redesign scores are also worse than for electronic linear actuators, because the system must fit inside the frame, which is very short on open space already. Linear actuators also allow for independent control of each rear wheel. Finally, linear actuators have superior feedback information, because they know actuator position whereas the steering rack motor would only know displacement and would lose the center position during a restart cycle.

Hydraulic actuators proved to be the worst option in most categories. The biggest issue is weight. At approximately 45lbs, the weight added would likely completely offset the performance advantage of four-wheel steering. Further, the packaging of the large components needed would be a severe challenge. The packaging has flexibility, because the actuators can mount outside the frame and the other components are connected by flexible hoses. However, it would be hard to find space for the pump, reservoir, and hoses in the tightly packed area we are working with. Cost is also non-competitive, because of the addition of the pump and reservoir. Feedback would also be challenging with the hydraulic actuators too because we would need additional sensors, introducing more cost and redesign.

3.4 PROPOSED PERFORMANCE MEASURES FOR THE DESIGN

- System complies with Formula SAE rules:
  - T6.5.5 Less than 6 degrees of rear wheel turn angle with mechanical stops
  - T6.5.5 Can be electronically actuated
  - T11.1.1 Steering fasteners must meet or exceed SAE Grade 5
  - IC4.4 Battery must be mounted to the frame and enclosed in a nonconductive container
- Active steering, turns in opposite directions at low speeds and in the same direction at high speeds
- Under 10 lbs. of added weight to the vehicle

- Must be compatible with existing frame and suspension geometry with minimum modifications
- Must have system feedback
- Should have a safety system that returns rear wheels forward facing orientation in the event of a power failure.
- Design is weatherproof and shockproof

3.5 DESIGN CONSTRAINTS

Table 6 Diagram of design constraints.

	Function	Safety	Economic	User needs and Requirements	
	Improve Steering response, enhance stability at high speeds, and improve turning radius at low speed	Returns to 2WS if electrical failure	Must fit within design budget for class and within FSAE budget	Feels predictable for the driver	**Use**
	Adapters for attaching linear actuators	Spring in parallel (need to consult steer by wire standards)	Reuse FSAE components. Substitute materials needed to meet weight requirements with heavier, cheaper materials.	Arduino or comparable controller with electrical components	**Production**
	Linear actuator size and packaging	Spring return for actuators	Low cost for non-safety essential components. Potentially add weight to reduce cost.	Proper actuator position and speed based on steering wheel angle and vehicle speed	**Planning**
4 Wheel Steering	MAX 6 degrees of steering angle in the rear - FSAE Rules	Maintain stability in the event of electrical failure	$400-450	Rate of rear wheel actuators	**Design**
FSAE	Aluminum Adapters	Purchase Actuator and electrical components. Develop safety and geometry	Closed course at competition and in testing. Open to the environment	Choose proper tools	**Design**
	Use stock from the machine shop	Reuse A-arms, uprights and suspension from previous FSAE vehicles	Components are exposed to environment and need weatherproofing	Make parts from same material and maximize stock usage	**Planning**
	Use CNC mill	Complicated components are purchased then modified. Small components are manufactured in house.	If components are not weather proof add weatherproofing	Manufacture duplicate parts at the same time on the CNC	**Production**
	Lightweight	Durable and easy to assemble	Operate smoothly under damp and dry conditions	Reduce cost by reducing materials	**Use**
	Materials	**Components**	**Environment of Use**	**Ecological/Life Cycle**	

4 EMBODIMENT AND FABRICATION PLAN

4.1 EMBODIMENT DRAWING

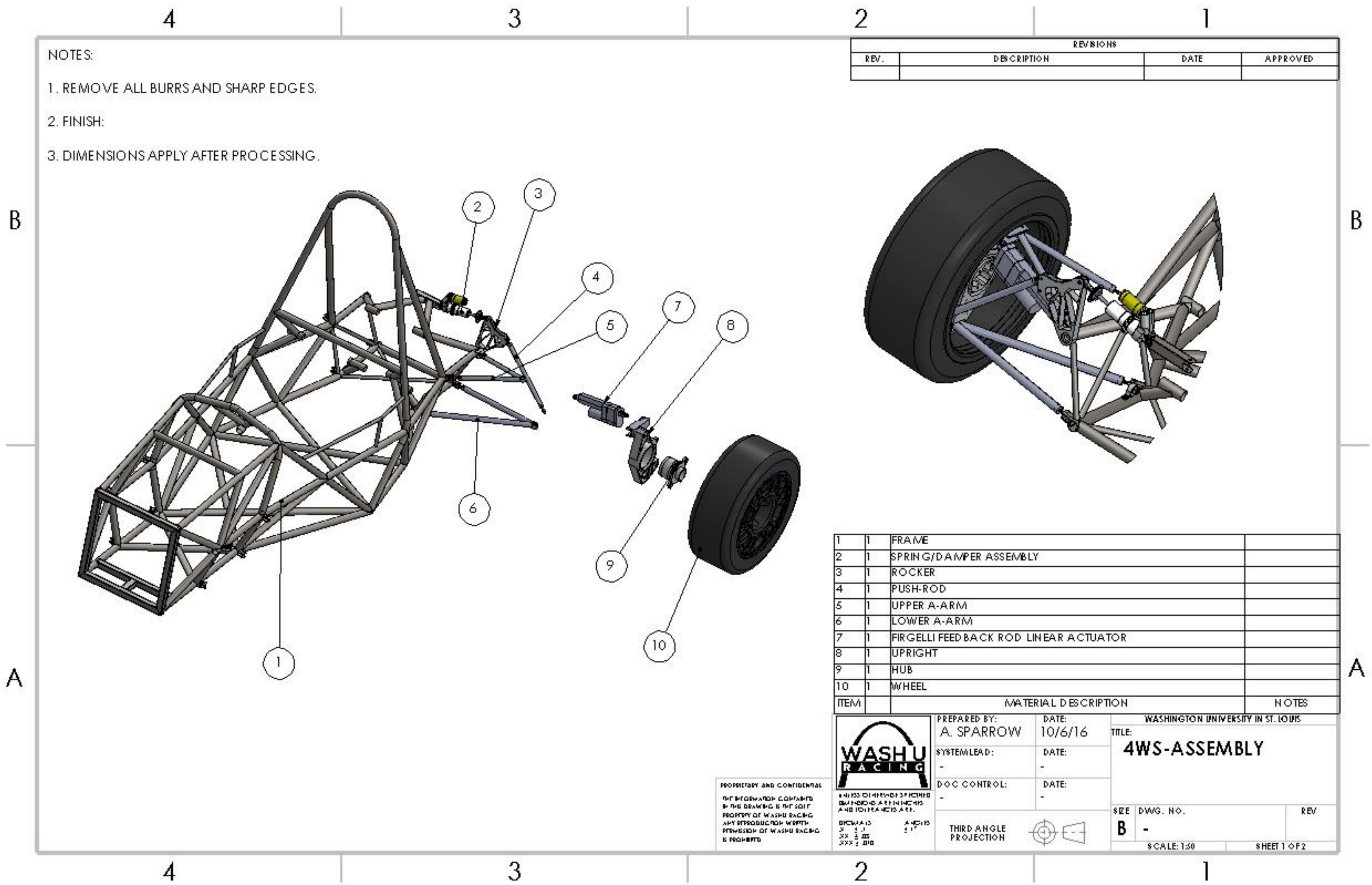

Figure 12 Draft full assembly drawing.

4.2 PARTS LIST

Table 7 Parts List.

	Part	Source Link	Supplier Part Number	Color, TPI, other part IDs	Unit price	Tax ($0.00 if tax exemption applied)	Shipping	Quantity	Total price
1	2" Stroke, 150lb Force Feedback Rod Linear Actuator	Firgelli Automation	FA-PO-150-12-02	Silver	$139.99	$0.00	$22.54	2	$279.98
2	12V DC Battery	Firgelli Automation	FA-BATTERY-12V	Black	$45.00	$0.00	$18.28	1	$45.00
3	Arduino Uno	—	Supplied	—	—	—	—	—	$0.00
4	Electrical Wires	—	Supplied	—	—	—	—	—	$0.00
5	Aluminum Stock for Adapters	—	Supplied	—	—	—	—	—	$0.00
6	Firgelli Technologies Linear Actuator Control Board	RobotShop	RB-Fir-121	Green Relay Switch Board	$40.00	$0.00	$0.00	2	$80.00
7	ABS Filament for 3D Printing	MakerBot.com	Supplied	Green	$18.00	$1.03	$12.97	1	$32.00
8	FSAE Car Frame and Suspension Assembly	—	Supplied	—	—	—	—	—	$0.00
Total :									$436.98
								Our Budget	$414.00

4.3 DRAFT DETAIL DRAWINGS FOR EACH MANUFACTURED PART

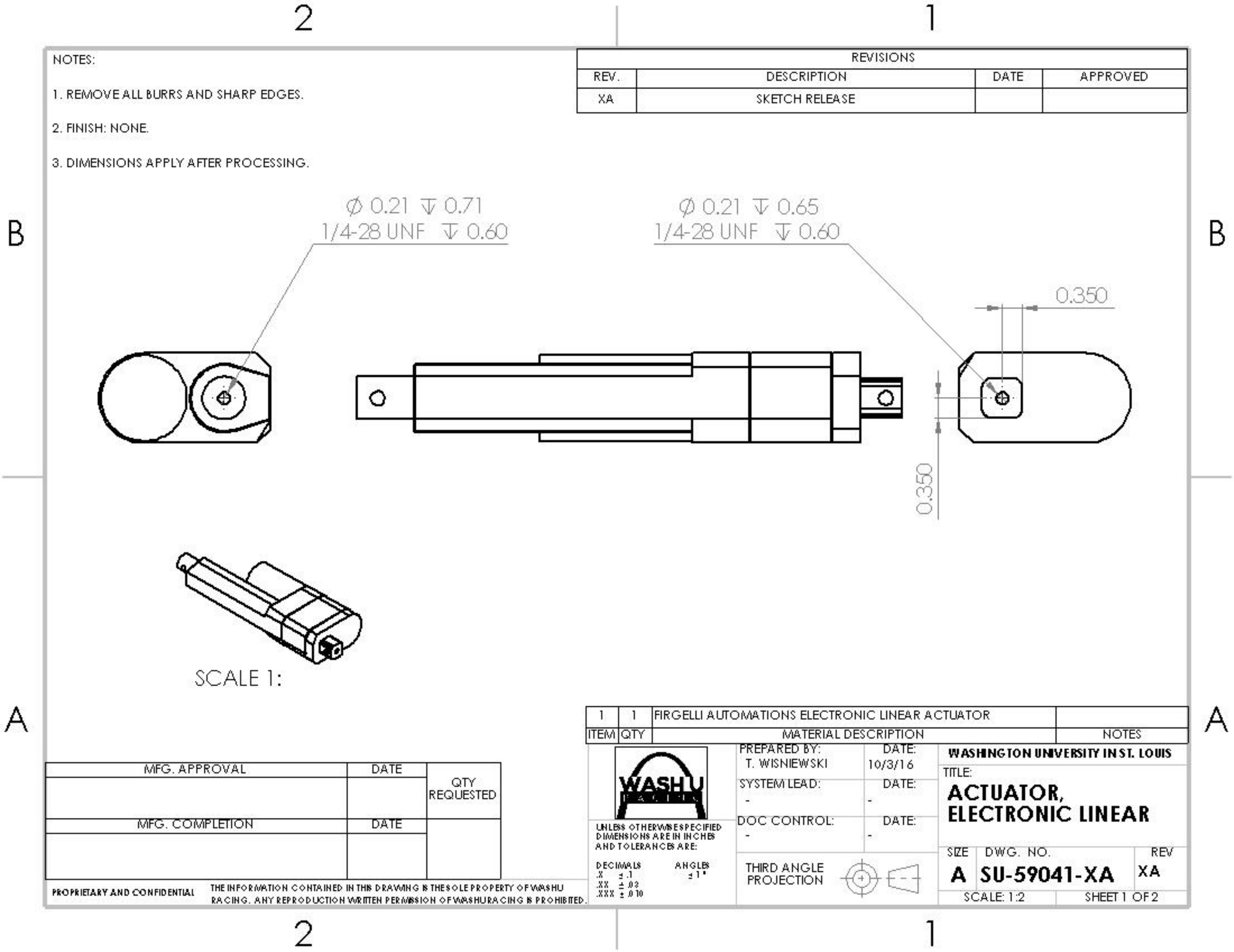

Figure 13 Draft drawing for electronic linear actuator modifications.

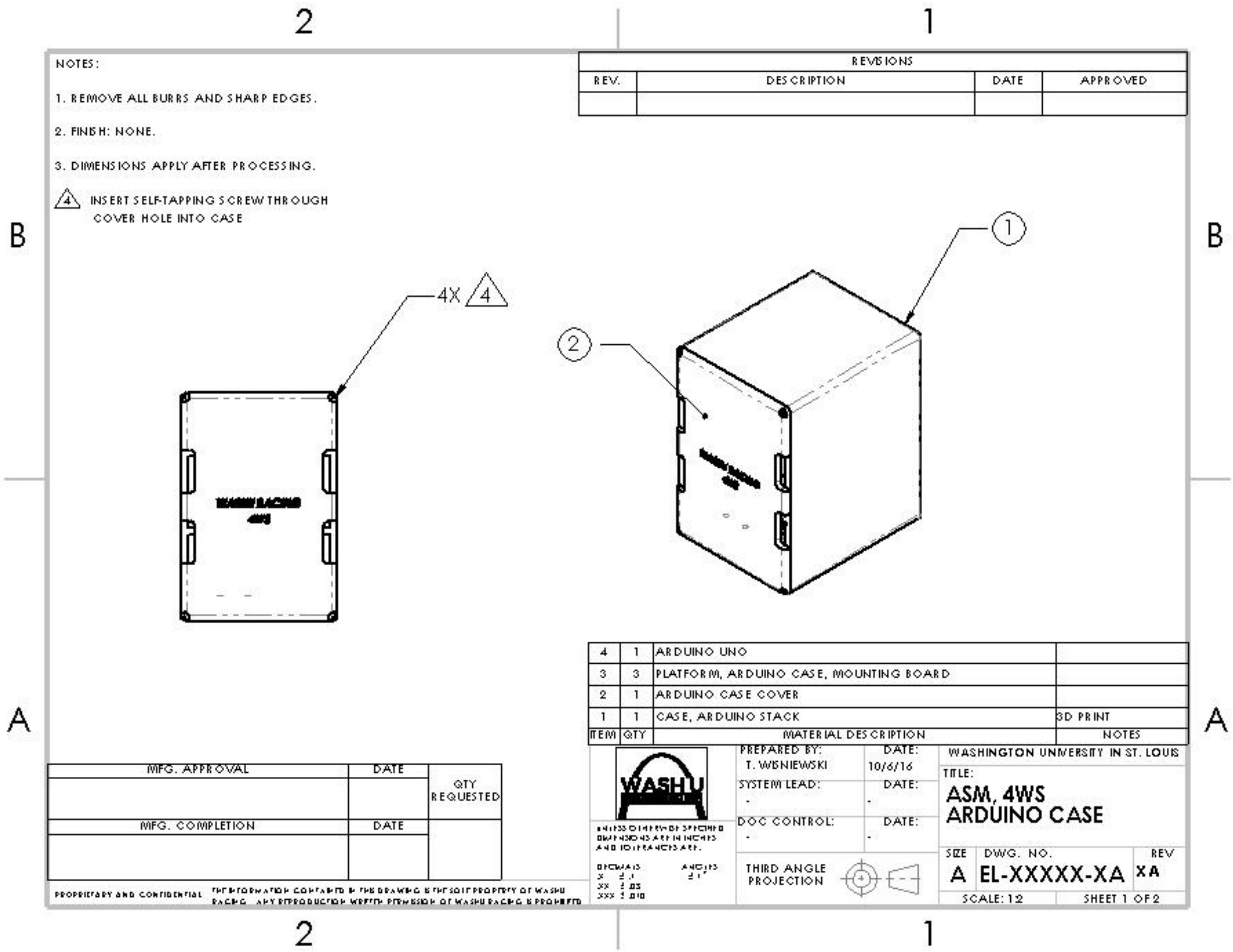

Figure 14 Draft assembly drawing for the Arduino case (sheet 1).

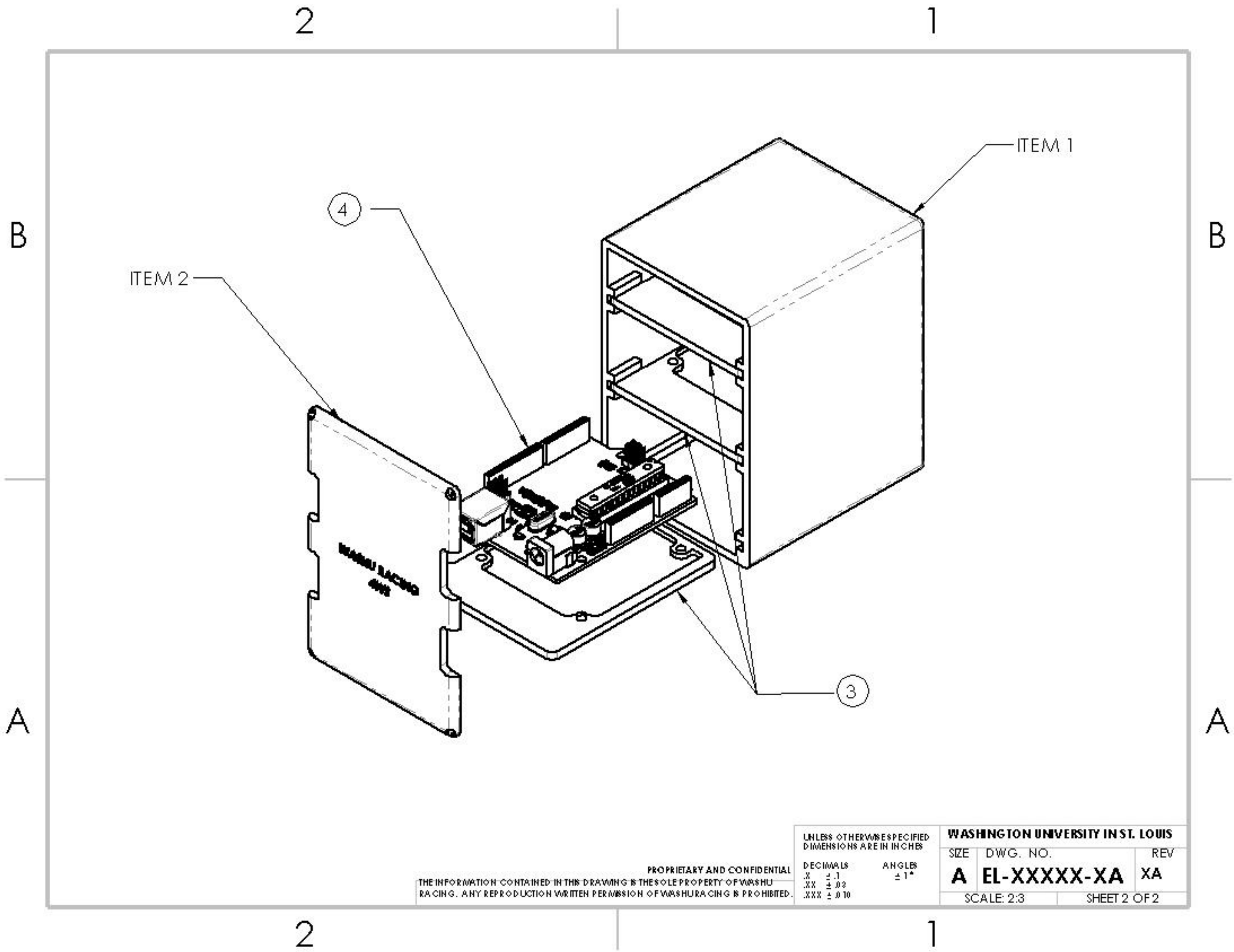

Figure 15 Draft assembly drawing for the Arduino case (sheet 2).

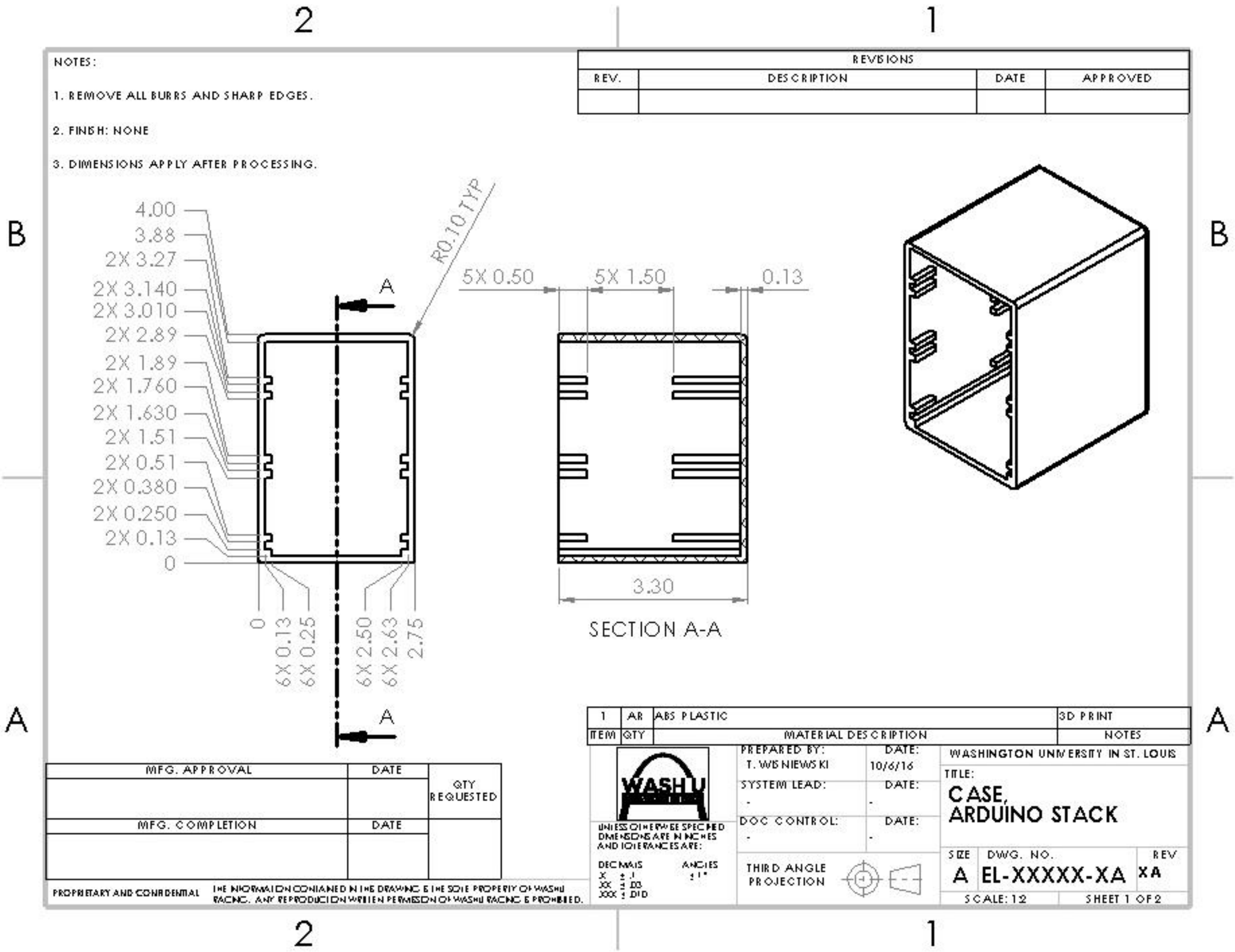

Figure 16 Draft Arduino case part drawing.

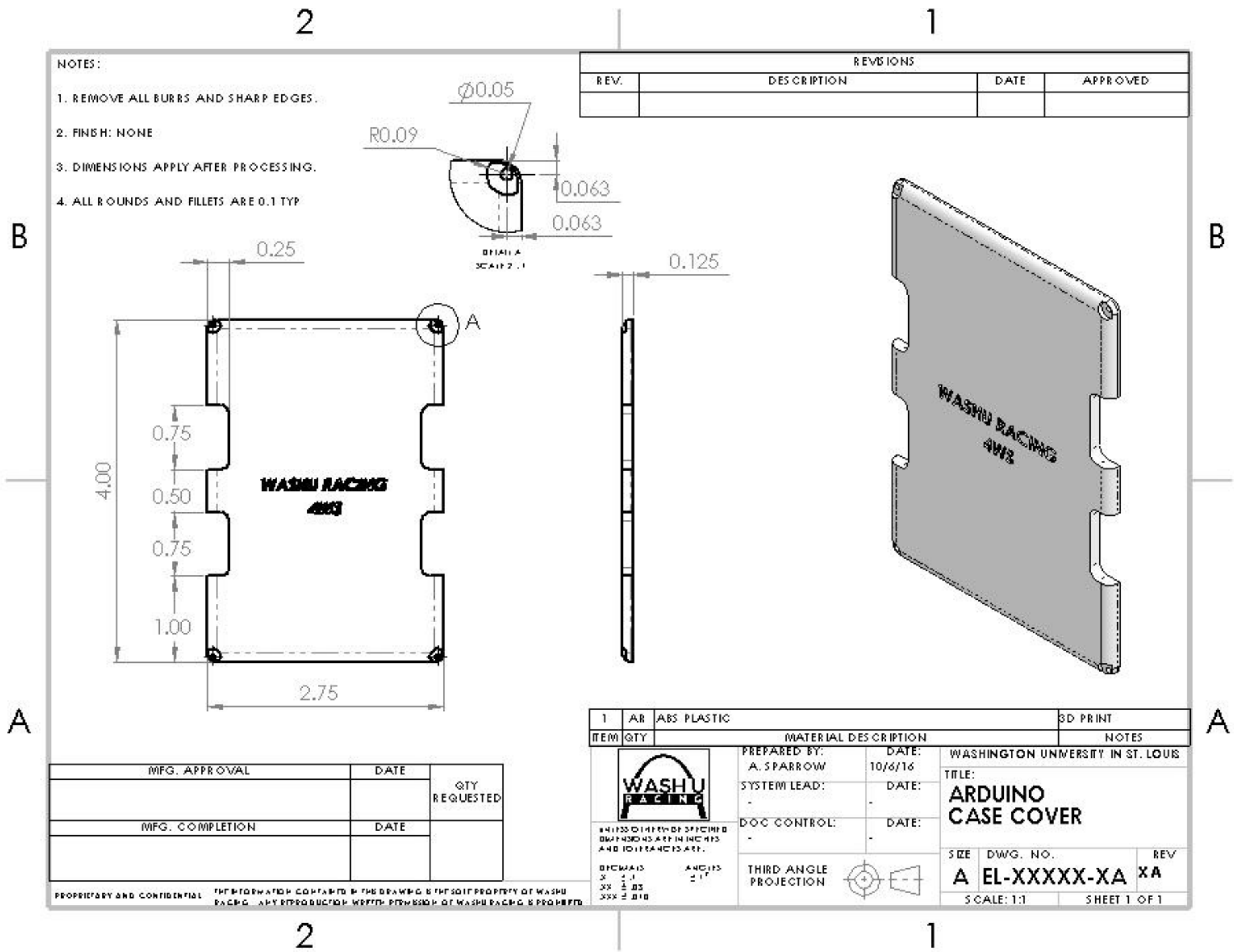

Figure 17 Draft Arduino case cover drawing.

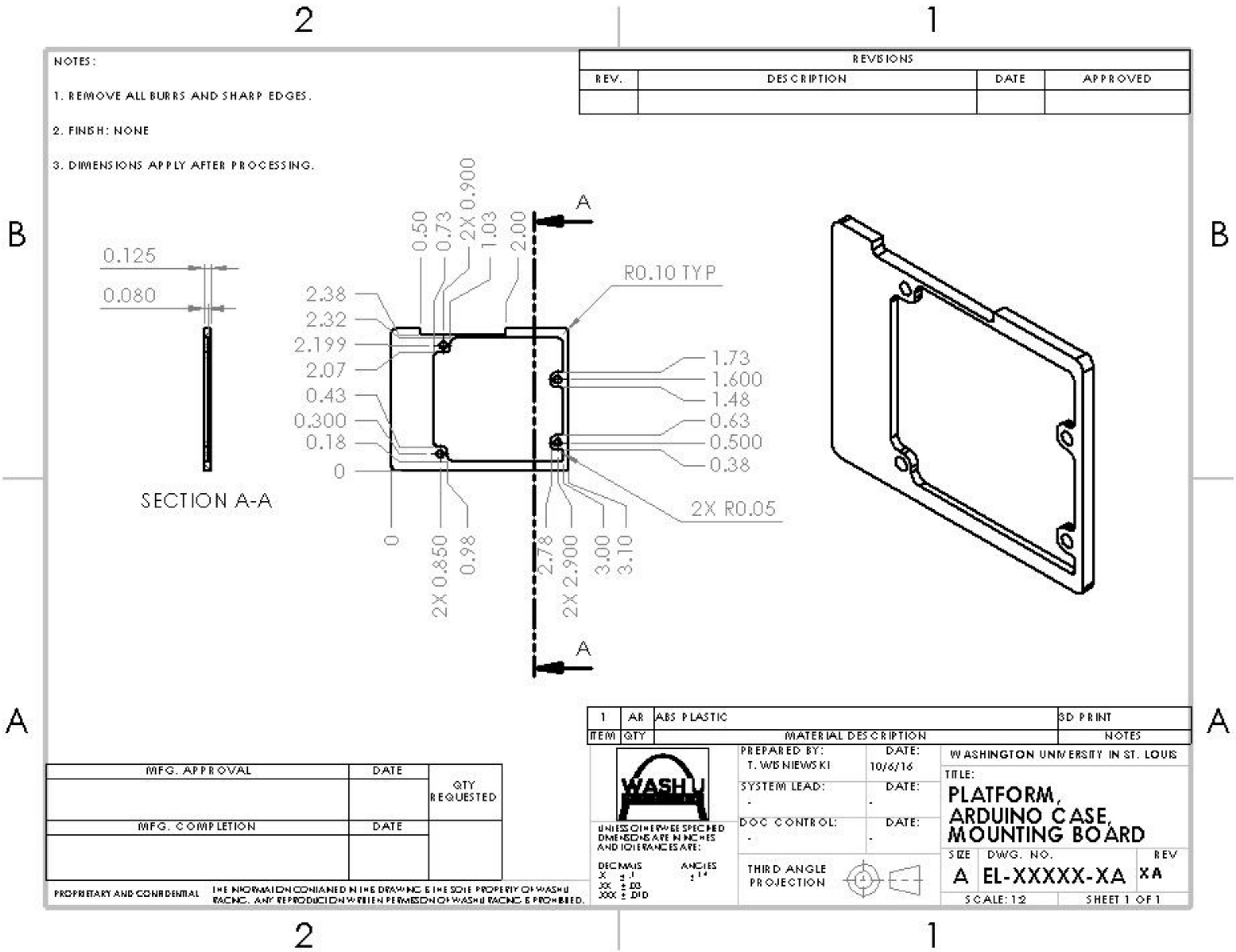

Figure 18 Draft Arduino case platform drawing.

4.4 DESCRIPTION OF THE DESIGN RATIONALE FOR THE CHOICE/SIZE/SHAPE OF EACH PART

4.4.1 Linear Actuators

Firgelli Automation feedback linear actuators were chosen for their desirable combination of light weight, built-in feedback, sufficient force and speed, and convenient size for replacing the toe links. At 2.7lbs, these linear actuators minimize the weight added to enable rear wheel steering, satisfying **Design Requirement 5.3**. However, the main reason the Firgelli linear actuators are a good choice is their reliable feedback from a built-in potentiometer (**Design Requirement 2.1**). The model selected is the 2in stroke feedback rod linear actuator, which 7.9in long retracted and 9.9in long at full extension. This length is well suited to replacing the 8.5in long toe-link rods, which constrain the rotation of the wheel on the current two-wheel steering design. This model's 150lb dynamic force output and .5in/second speed is sufficient for this application to satisfy **Design Requirements 1.2, 1.3, and 1.4**. Finally, the only modification is the addition of tapped holes at each of the linear actuator. These tapped holes allow for the insertion of rod ends with spherical bearings to attach the linear actuator to the frame and wheel upright using the same mounts as the toe-link. This solution was chosen to allow the linear actuator to move up and down with the wheel and minimize weight compared to a design that adds adapters to attach the linear actuators to the spherical bearings.

4.4.2 Arduino Uno and Firgelli Linear Actuator Control board

The Arduino Uno microcontroller was chosen for its small size, low power demand, and simple programming. The 2in x 3in size of the Arduino Uno enables a compact housing and flexibility in location on the car, reducing weight (**Design Requirement 5.3**) and improving serviceability (**Design Requirement 4.3**). The forces required to turn the wheels consume a significant amount of power, so power demand must be minimized from the control system. The simplicity of programming an Arduino is another advantage, because this will reduce the likelihood of programming errors, simplify troubleshooting, and enable greater capabilities than a more specialized controller would offer. The Firgelli Technologies linear actuator control boards separate the power supply of the linear actuators from the Arduino's power supply. This is needed to protect the Arduino from the high power required by the linear actuators. These control boards also ensure the signals from the Arduino are interpreted properly by the linear actuators.

4.4.3 12V DC Battery

The Firgelli Automation 12V DC battery will be used to power the linear actuators and control system on the prototype. This battery is specialized for linear actuators, ensuring it will have sufficient output for the selected linear actuators. Since this battery is designed for the Firgelli linear actuators, it is also ensured that the battery will not damage the actuators by supplying an excessive power. For this rolling prototype, which lacks the engine as a power source for a final product, the Firgelli specialized battery reduces the potential for issues with supplying power to system.

4.4.4 Arduino Case Assembly

The Arduino Case was chosen in order to satisfy our Design Requirements. It was desired to keep the system weatherproof (**Design Requirement 4.1)** and accessible (**Design Requirement 4.3**). for various driving conditions. The box allows an Arduino and 2 relay boards to be contained securely out of the elements and be mounted to the car. The Arduino mount is critical for providing electronic control for the electronics systems. Each board can be attached to a board mount that slide into the case. Relief cuts were included in mounting boards to allow for protruding leads from the boards. Small slits were included in the mounting boards to allow wires to be run between boards. Additionally, the case cover allows the wires to exit the case in order to run to their corresponding components. The Arduino Case will be 3D printed in ABS plastic to be lightweight, easy to manufacture and insulated. The Arduino Case Assembly will be mounted to the frame of the car along the left side inside the side-pod where other electrical components such as the Engine Control Unit (ECU) are already mounted.

4.5 GANTT CHART

A Gantt chart was developed to help organize tasks and determine dependencies between them. The tasks were compiled in Table 8, and are graphically represented in Figure 19.

Table 8 Organization of tasks, duration of tasks, and assignment of tasks used to develop a Gantt chart.

Task Number	Design Requirement	Task Name	Duration	Start	Finish	Predecessors	Assigned To
1		Design Approval	7 days	Wed 8/31/16	Thu 9/8/16		All
2		Background Study	9 days	Wed 8/31/16	Mon 9/12/16		All
3		Standard Selection	20 days	Wed 9/7/16	Tue 10/4/16		All
4		Functional Requirements	5 days	Mon 9/12/16	Fri 9/16/16		All
5		Design Requirements	3 days	Mon 9/19/16	Wed 9/21/16	4	All
6		Embodiment and fabrication Plan	12 days	Thu 9/22/16	Fri 10/7/16	5	All
7	1.2	CAD Linear Actuators	3 days	Mon 9/19/16	Wed 9/21/16	4	Andrew
8	5.3	CAD layout	7 days	Mon 9/19/16	Tue 9/27/16	4	Andrew
9		Design Review 1	0 days	Fri 9/30/16	Fri 9/30/16		
10	1.2	Working CAD Assembly	10 days	Wed 9/28/16	Tue 10/11/16	8	Andrew
11	5.3	CAD Adapters	4 days	Wed 9/28/16	Mon 10/3/16	8	Andrew
12	1.3	Order Linear Actuators	6 days	Tue 10/4/16	Tue 10/11/16	11	Phil
13	1.1	Select Battery	3 days	Tue 10/4/16	Thu 10/6/16	11	Andrew
14	1.1	Order Battery	4 days	Fri 10/7/16	Wed 10/12/16	13	Phil
15	2.4	Order Arduino	3 days	Tue 10/4/16	Thu 10/6/16	11	Phil
16	5.3	CAD Arduino and Battery Mount	4 days	Fri 10/7/16	Wed 10/12/16	15	
17	3.1	Design Safety Mechanism	10 days	Wed 10/12/16	Tue 10/25/16	12	Phil
18	4.3	Reassemble Suspension and Frame	5 days	Wed 10/12/16	Tue 10/18/16	10	Phil
19	4.3	Assemble Rear Differential and Driveshafts	6 days	Wed 10/19/16	Wed 10/26/16	18	Andrew
20	2.6	Develop Arduino Program	15 days	Fri 10/7/16	Thu 10/27/16	15	Theo
21	2.2	Install and Calibrate Steering angle sensor	8 days	Wed 10/19/16	Fri 10/28/16	18	Theo

22	2.3	Install and Calibrate Wheel Speed Sensors	8 days	Wed 10/19/16	Fri 10/28/16	18	Andrew
23		Design Review 2	0 days	Fri 11/4/16	Fri 11/4/16		
24	1.3	Manufacture Adapters	15 days	Thu 10/13/16	Wed 11/2/16	16	
25	5.3	Manufacture Mounts	10 days	Thu 10/13/16	Wed 10/26/16	16	
26	3.1	Manufacture Safety Mechanism	10 days	Thu 10/13/16	Wed 10/26/16	16	
27	2.6	Install Arduino	4 days	Thu 11/3/16	Tue 11/8/16	24	
28	4.3	Install Wheels and Tires	1 day	Wed 11/9/16	Wed 11/9/16	27	
29	2.4	Test Programming	3 days	Wed 11/9/16	Fri 11/11/16	27	
30		Finished Prototype Demonstration	3 days	Mon 11/14/16	Wed 11/16/16	29	
31		Finalize Project Report	10 days	Mon 11/14/16	Wed 11/30/16	29	
32		Final Presentation	5 days	Thu 11/17/16	Mon 11/28/16	30	
33		Teardown	5 days	Thu 12/1/16	Wed 12/7/16	31	

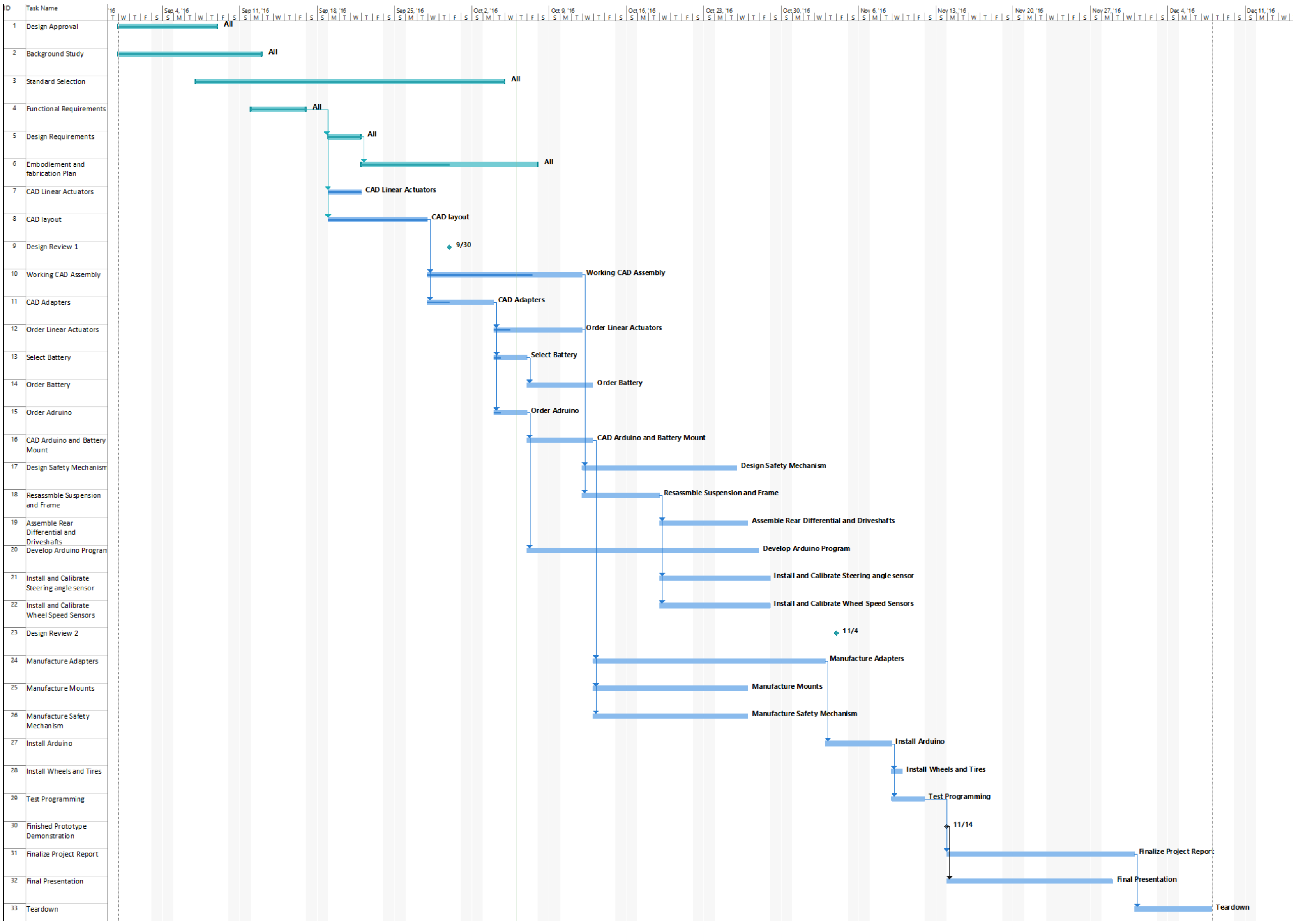

Figure 19 Gantt Chart.

5 ENGINEERING ANALYSIS

5.1 ENGINEERING ANALYSIS PROPOSAL

This section is intentionally left blank.

5.2 ENGINEERING ANALYSIS RESULTS

5.2.1 Motivation

The three studies that were important to carry out before any manufacturing took place included upright adapter finite element analysis, clearance study of the half-shaft and hub, motion study of actuator movement in the suspension assembly, and electronics circuit design study. The result of these studies is crucial to determining the feasibility and limitations of the design chosen.

5.2.1.1 Upright Adapter FEA

Finite element analysis is important to check existing parts where loading was expected to change. A stress analysis can be used to determine possible locations of failure in the system. Finding that the part failed under expected loading would require the adapter to undergo design changes to make it more robust.

5.2.1.2 Half-Shaft Clearance Study

The clearance study is to determine whether there would be interference between the half shaft and the hub at the maximum six degrees of rear wheel turn which is allowed by FSAE rules. If there is a failure in the clearance study, there would either need to be limitations on the motion of the wheel to prevent interference.

5.2.1.3 Assembly Motion Study

The motion study of the linear actuators is to determine what motion of the linear actuator in position of the toe link would induce on the wheel. Before assembly of the system, consequences of dynamically adjusting the toe of the rear wheels should be discovered and accounted for.

5.2.1.4 Circuit Analysis

Circuit design and analysis needed to be done to ensure that the circuit could run the actuators simultaneously and operate on Arduino commands.

5.2.2 Summary statement of analysis done

5.2.2.1 Upright Adapter FEA

FEA Analysis was carried out where the loading on existing components changed. In the new assembly with the actuators, the pushrod of the suspension is replaced with the actuator and has a new load applied to the upright adapter. This was seen as a new weak point and a worst-case scenario was carried out which defined the wheel position to be locked and have the full 150lbf of the actuator pushing on the adapter of the upright. This is worst-case because when the car is in motion the loads experienced by the adapter from the actuator are much less because the vehicle is in motion; turning wheels in motion takes less force than static turning.

5.2.2.2 Half-Shaft Clearance Study

Also, an interference check of the half-shaft and the hub at the maximum toe angle of 6 degrees was performed to check for clearance and resulted in a max allowable toe angle much larger than expected.

5.2.2.3 Assembly Motion Study

The motion study was completed by constraining suspension points to sketch points on the frame. Additionally, the damper was allowed to study to include suspension travel. These constraints allowed for motion within the CAD model.

5.2.2.4 Circuit Analysis

The circuit was designed and tested on Autodesk Circuits. The circuit was developed to be capable of turning the motors on and off as well as run in both directions.

5.2.3 Methodology

5.2.3.1 Upright Adapter FEA

The FEA was carried out in SolidWorks such that the upright was fixed and that the adapter was connected using a bolt connection. With the upright fixed, a 150 lbf load was distributed across the bolt hole of where the actuator would attach to simulate the pushing of the actuator onto the adapter. A fine mesh was applied for an increase in accuracy of the analysis and results were obtained.

5.2.3.2 Half-Shaft Clearance Study

An interference check was also carried out in SolidWorks to see the maximum toe angle that can be achieved between the hub and the half-shaft such that the standard maximum toe angle of 6 degrees could be achieved. Interference of these two crucial parts would be catastrophic for the vehicle and may result in many part failures.

5.2.3.3 Assembly Motion Study

SolidWorks Motion was used to perform the motion study. A motor feature was applied to the actuator rod face which initiated the motion in the study.

5.2.3.4 Circuit Analysis

Autodesk Circuits was used to build and analyze our circuit with connected to an Arduino to see if system responds as expected. The Arduino code used in the simulation can be found in Appendix D. The following link will take you to the analysis: https://circuits.io/circuits/3135746-two-linear-actuator-circuit-design-simulation.

5.2.4 Results

5.2.4.1 Upright Adapter FEA

The results showed that the adapter had a maximum Von Mises stress of approximately 48MPa where the yield stress of the aluminum is 55MPa. This occurred near the nearest bolt hole location on the adapter towards the applied load. The results make sense and present a small factor of safety of the analysis.

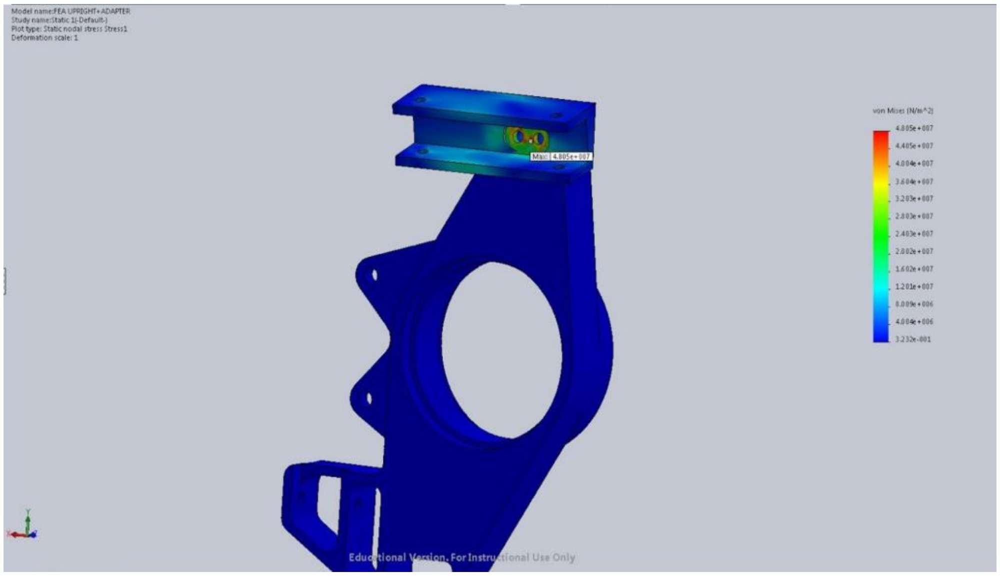

Figure 20 FEA analysis on the upright adapter.

5.2.4.2 Half-Shaft Clearance Study

The clearance check between the half shafts and the hub resulted in a maximum toe angle of approximately 10 degrees until any interference occurred. This means the wheel has plenty of freedom to turn appropriately.

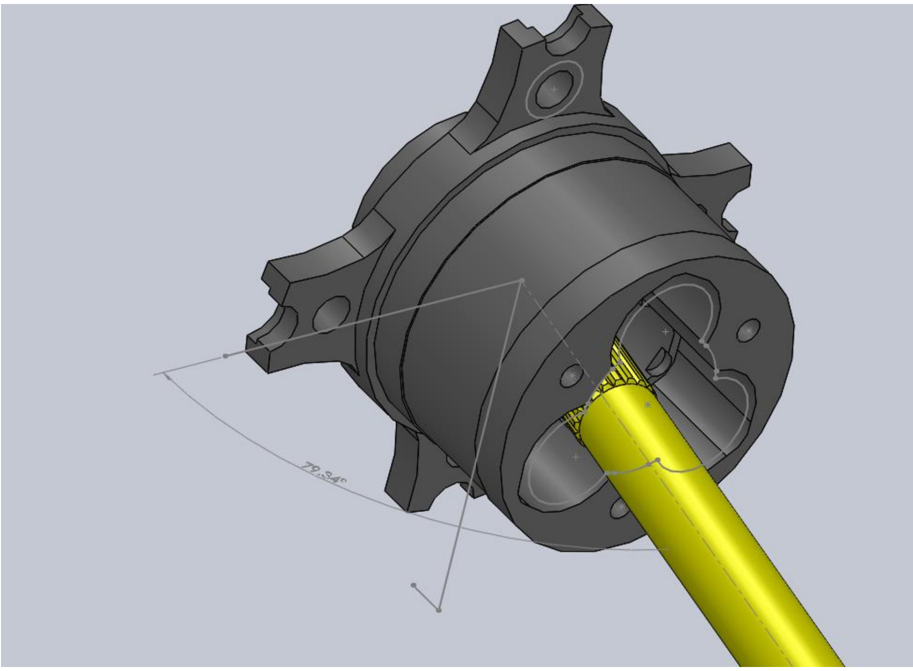

Figure 21 Clearance check between the half-shaft and the hub.

5.2.4.3 Assembly Motion Study

Motion study of the system showed unusual loading of the suspension components. For the scope of this project this is something to take into the future when designing the frame and suspension in accordance to implementing four-wheel steering. The link to the video of the study is attached here:

https://drive.google.com/open?id=0B2Wa0DGxtAqhLTJ0SGZXc1VJYTg

5.2.4.4 Circuit Analysis

Circuit analysis, using Autodesk Circuits, was used to develop a circuit that would run the linear actuators in a way that separated them from the Arduino. The Arduino is does not support enough voltage to power the actuators directly which would require them to be driven by a separate circuit which was controlled by the Arduino. The circuit shown in Figure 22 is the initial design to test that the actuators would turn on and off as well as change direction based on Arduino commands.

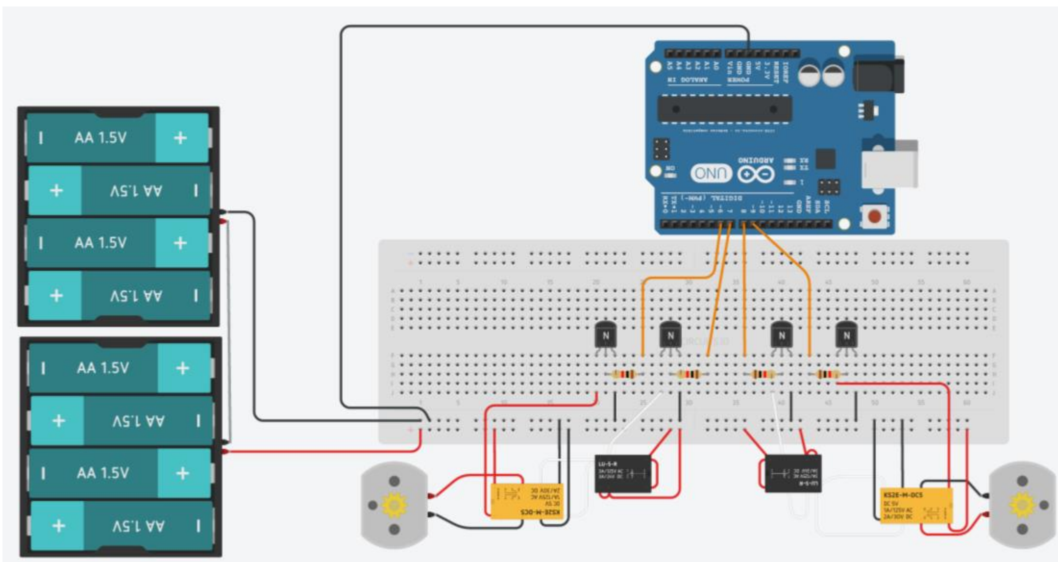

Figure 22 First circuit design used to test that actuators would turn off and on as well as change directions.

5.2.5 Significance

5.2.5.1 Upright Adapter FEA

These results give clearance for the final prototype to proceed within the scope of the project. Going forward from the prototype, applying this to the full functioning car for further testing and implementation would require the adapter to be increased in thickness to improve the factor of safety. The current part's approximately 1.5 factor of safety is uncomfortably small for use on a driving car, but will be sufficient for the loading this prototype will experience.

5.2.5.2 Half-Shaft Clearance Study

The results of the half-shaft clearance study indicate there will be no issues with the half-shaft contacting any part of the hub in the range of motion applied to the system. Even increasing turn angle to the maximum allowed by the system's codes and standards would not risk any interference. No changes would be needed to the drivetrain system to apply the four-wheel steering system to a driving car.

5.2.5.3 Assembly Motion Study

The results of the full system motion study indicated the desired steering angles are easily achievable with the chosen linear actuators and suspension geometry of the existing parts. For the scope of this prototype the motion is acceptable, because there is no interference between the linear actuator and the suspension or frame. However, for later application to a fully functional Formula SAE car the rear suspension geometry should be redesigned to reduce or eliminate the vertical movement caused by rotating the wheel.

5.2.5.4 Circuit Analysis

Based on the simulation the basic principles of the circuit are correct. However, the components used in the simulation are not exactly the same as used in the prototype. For example, some 5V components were used in the simulation in place of the 12V parts used in the final prototype. This should not undermine the results, because the components behave the same way within the system

5.2.6 Summary of code and standards and their influence

One of our main standards is from the FSAE Racing Rule Book and it states that if rear turning is to occur, a maximum toe angle of 6 degrees applies. This has great influence on the programing of the actuators such that we must limit their turning capacities to 6 degrees either toe in or toe out. Much geometry and analyses must be done to see how far the actuator must extend to reach these limits. In terms of the mechanical design, this standard does not have any influence in comparison to the programing design.

5.3 RISK ASSESSMENT

5.3.1 Risk Identification

There are a variety of pressures on the project that introduce barriers to successfully completing the project. Revisiting the design metrics used to choose the direct electronic linear actuator design option reveals speed, cost, amount of redesign, and system feedback are all sources of risk. Weight and packaging do not present significant risk, because the simplicity of this design option ensures weight gain will be minimal and the actuators have been sized to directly replace the existing toe-links. For Speed, it is known the actuator have a sufficient feed rate to steer at pace with the front wheels. However, it is unknown how quickly the actuators will respond to and input or how effectively the Arduino can be programmed to follow front steering inputs. Cost introduces significant risk, because the budget is sufficient to complete the project only if there are no unexpected expenses. An unforeseen actuator failure for example would be a major setback. The amount of redesign portion of the project goals is heavily dependent on the availability of a complete suspension and frame assembly from the 2015 Formula SAE racecar. Finally, system feedback risk ties back to the Arduino programming challenge. Feedback from the linear actuator is essential to controlling steering angle, so it is vital to the project that the Arduino program be able to interface with the actuator’s built-in feedback. Finally, time is another significant constraint not covered by the design metrics. 3D printing and Arduino programming are the time intensive steps we must account for. Therefore, the following risks were identified:

- Actuator Response Time
- Arduino Programming
- Linear Actuator Failure
- Missing Suspension components

- Theft or misplacing of parts
- 3D Printing Time

5.3.2 Risk Impact or Consequence Assessment

5.3.2.1 Actuator Response Time

- Impact = 3: Working prototype's steering response time may not be fast enough to achieve the desired responsive and natural handling feel. This portion is not essential to the four-wheel steering proof of concept; however, the goal is for the working prototype to require minimal design changes to be applied to a driving car.
- Likelihood = 2: Initial testing of the actuators revealed a delay between target position and actual position of less than .25 seconds. This is faster than the duration of a typical steering input, so it is unlikely this will prove insufficient for responsiveness.

5.3.2.2 Arduino Programming

- Impact = 4: Programming is the key to controlling the linear actuators. A sophisticated program is required to convert a front steering input into a target position for the rear steering, adjust steering behavior based on vehicle speed, use feedback to precisely control rear steering angles, and coordinate both linear actuators. The proof of concept does not require a fully developed control system, but each of those functions must be present for the goals to be achieved.
- Likelihood = 3: The built-in feedback and circuitry designed for controlling linear actuators with an Arduino ensure all of the desired functions are possible. However, developing and refining the program will be a significant challenge. We expect it is moderately likely the Arduino program will not be able to achieve the desired level of control.

5.3.2.3 Linear Actuator Failure

- Impact = 4: The linear actuators are the most expensive component of the project and also require the most modification to be applied to the car. Two linear actuators are also essential to demonstrating the effectiveness of the four-wheel steering system. Linear actuator failure would either put the project over budget or prevent the working prototype from performing as desired.
- Likelihood =5: At a minimum the actuators will require partial disassembly to add threaded holes at either end for attaching rod end bearings for attachment to the frame and suspension adapter. Significant disassembly will be required to explore the possibility of designing a fail-safe mechanism into the actuator. Between disassembly and power supply, there is a high likelihood an actuator could be damaged or broken.

5.3.2.4 Missing Suspension Components

- Impact = 2: Major suspension components such as wheels, uprights, hubs, and control arms were secured at the beginning of the project, so missing components will be limited to more minor components. Therefore, machining replacements should not prove to be a major setback.
- Likelihood = 3: It is likely some components will need to be replaced due to damage or being misplaced. However, we took inventory of the existing parts before starting the project, so it is only moderately likely missing suspension components will prove to be a larger challenge than anticipated.

5.3.2.5 Theft or misplacing parts

- Impact = 4: Several parts such as linear actuators, battery, suspension, and 2015 FSAE frame would be expensive and/or time consuming to replace in the event of theft or misplacing.
- Likelihood = 1: All components are securely stored either in the WashU Racing garage or Urbauer cage, so theft is unlikely. Misplacing parts is also unlikely, because we will be careful to keep parts together.

5.3.2.6 3D Printing:

- Impact = 1: The 3D printed boards and mounts for the electronics is not essential to the functionality of the system. If these could not be printed, the electronics could still be attached to the car through alternative means. The electronics would not be weatherproofed in that case, which was a design goal due to the need to operate in rain conditions.
- Likelihood = 3: The total printing time of the parts is nearly 20 hours, so finding time on the CAD lab's printers could prove challenging. If there are printing errors and parts need to be remade, it is moderately likely there would not be time to print the parts.

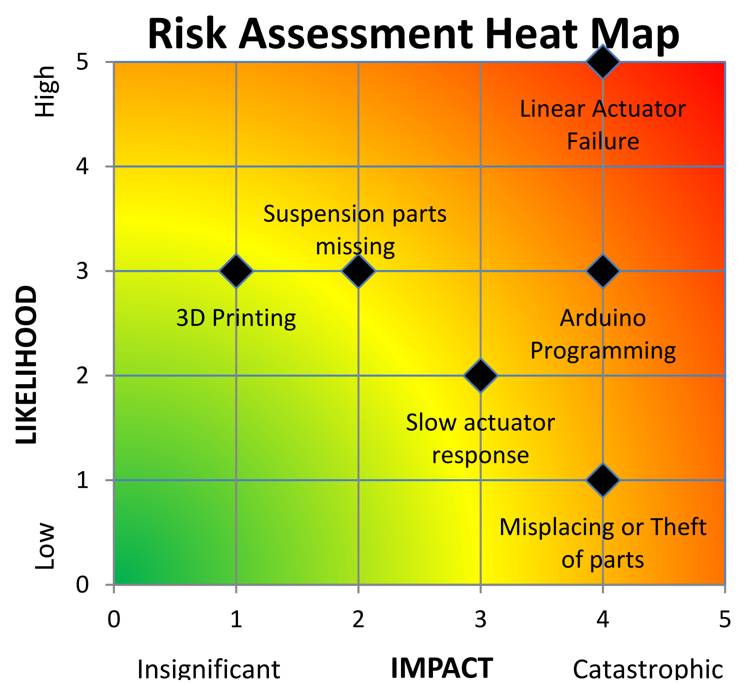

Figure 23 Risk Assessment Heat Map.

5.3.3 Risk Prioritization

Risks were prioritized in accordance with the Risk Assessment Heat Map result. The risks with the greatest impact on our ability to successfully build a working four-wheel steering system and high likelihood of occurring are the highest priority. Our analysis of these risks determined high impact risks are a stronger priority for this project than high likelihood. Impact of the risks are cases that would prevent the prototype from being able to steer the rear wheels, the key capability needed for the prototype to successfully fulfill our design metrics.

1. Linear Actuator Failure
2. Arduino Programming
3. Suspension Parts Missing
4. Slow Actuator Response
5. Misplacing or Theft of parts
6. 3D Printing

6 WORKING PROTOTYPE

6.1 A PRELIMINARY DEMONSTRATION OF THE WORKING PROTOTYPE

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6.2 A FINAL DEMONSTRATION OF THE WORKING PROTOTYPE

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6.3 FINAL PROTOTYPE IMAGES

Figure 24 Final prototype.

Figure 25 Low speed left turn.

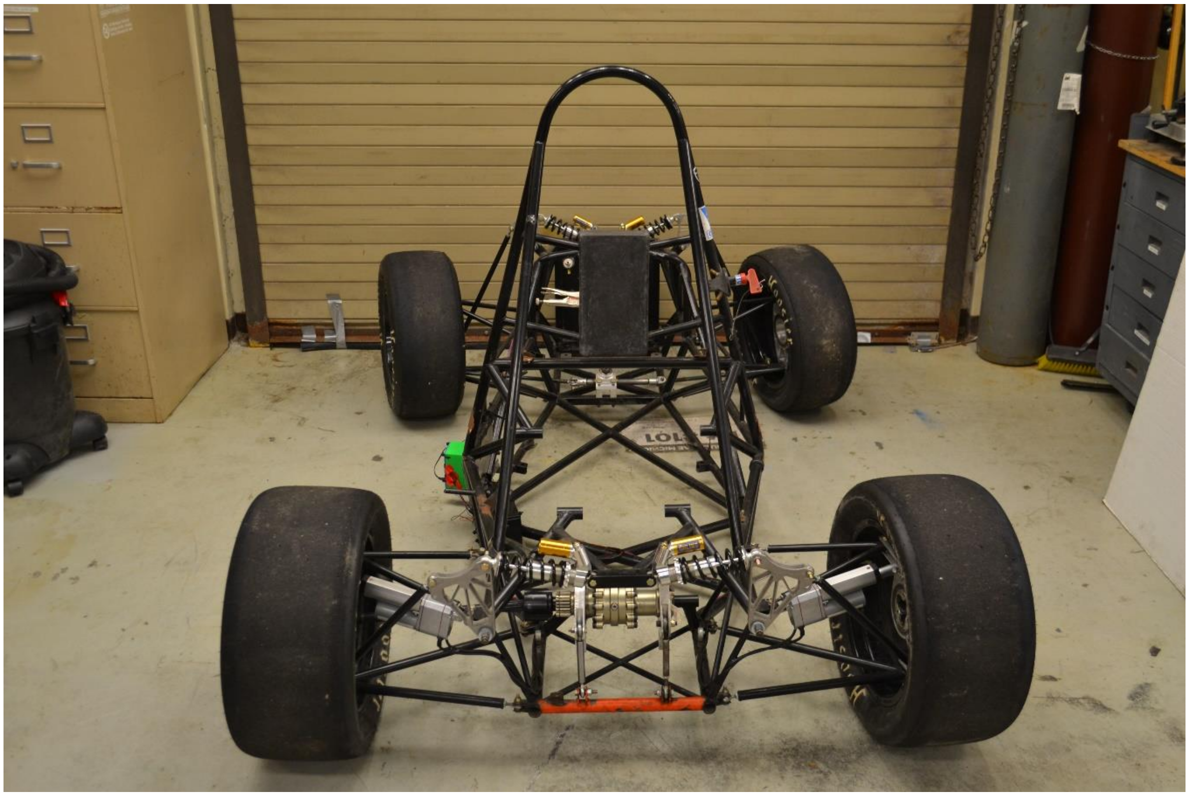

Figure 26 High speed left turn.

6.4 A SHORT VIDEOCLIP THAT SHOWS THE FINAL PROTOTYPE PERFORMING

Figure 27 Photo and link to a video of the working prototype https://youtu.be/uG7amaa2T_I.

6.5 ADDITIONAL IMAGES

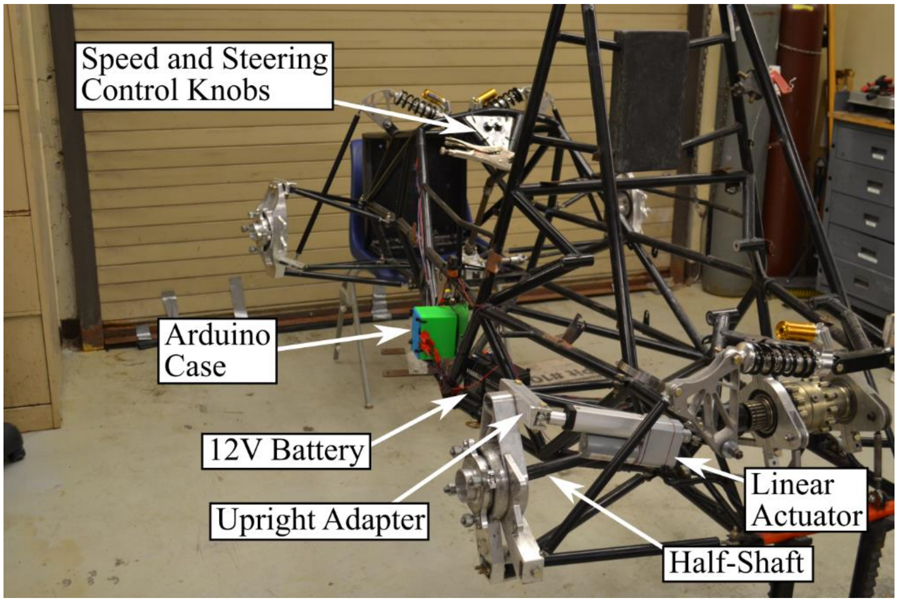

Figure 28 Prototype assembly without wheels.

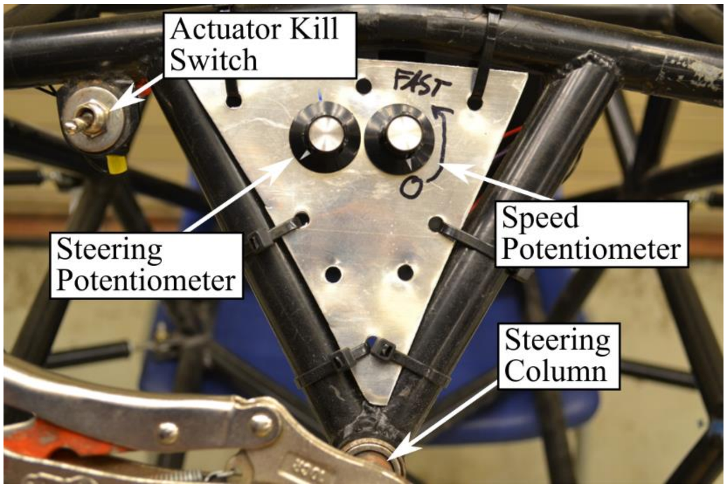

Figure 29 Steering and speed control knobs.

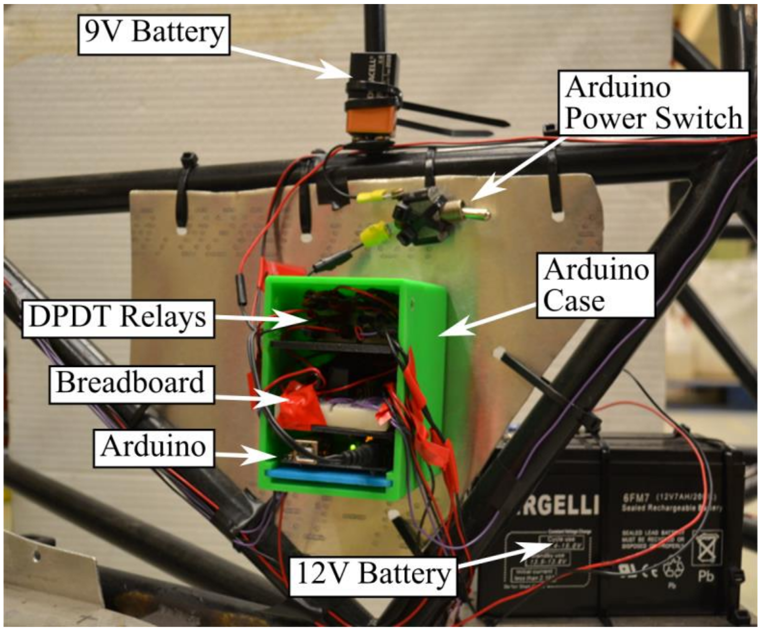

Figure 30 Arduino case in final prototype.

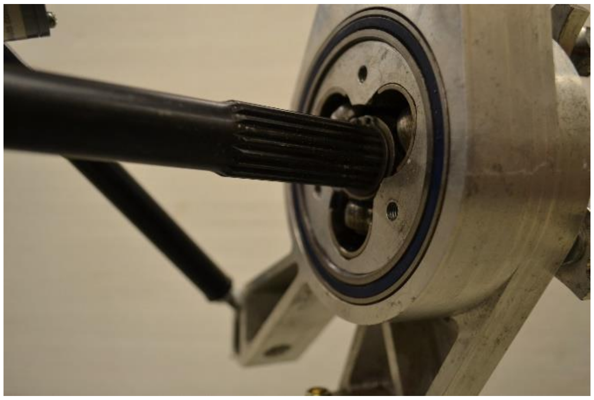

Figure 31 Half-shaft clearance.

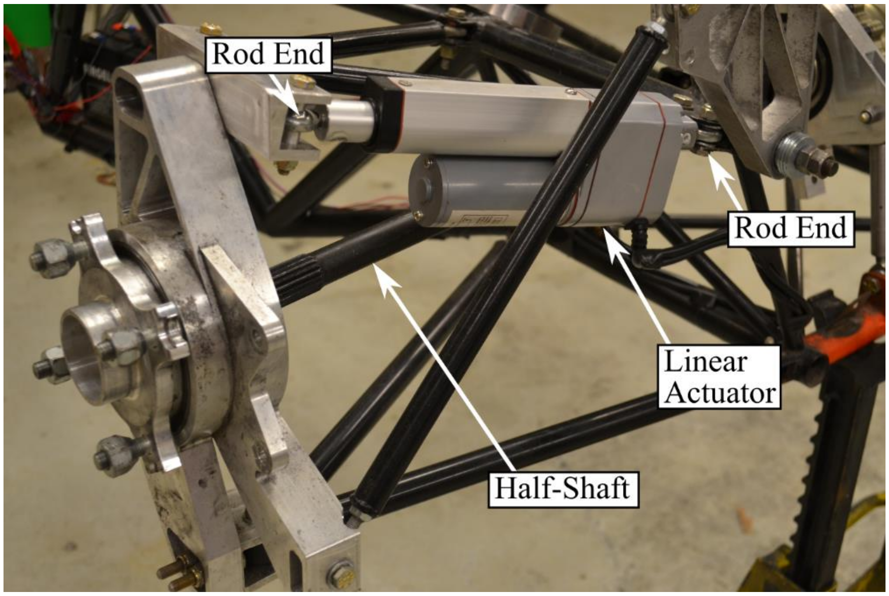

Figure 32 Actuator in assembly.

Figure 33 Turning Test in low speed Ackerman steering setting, radius measured 15 ft.

Figure 34 Turning Test with standard steering (no rear wheel steering), radius measured 20 ft.

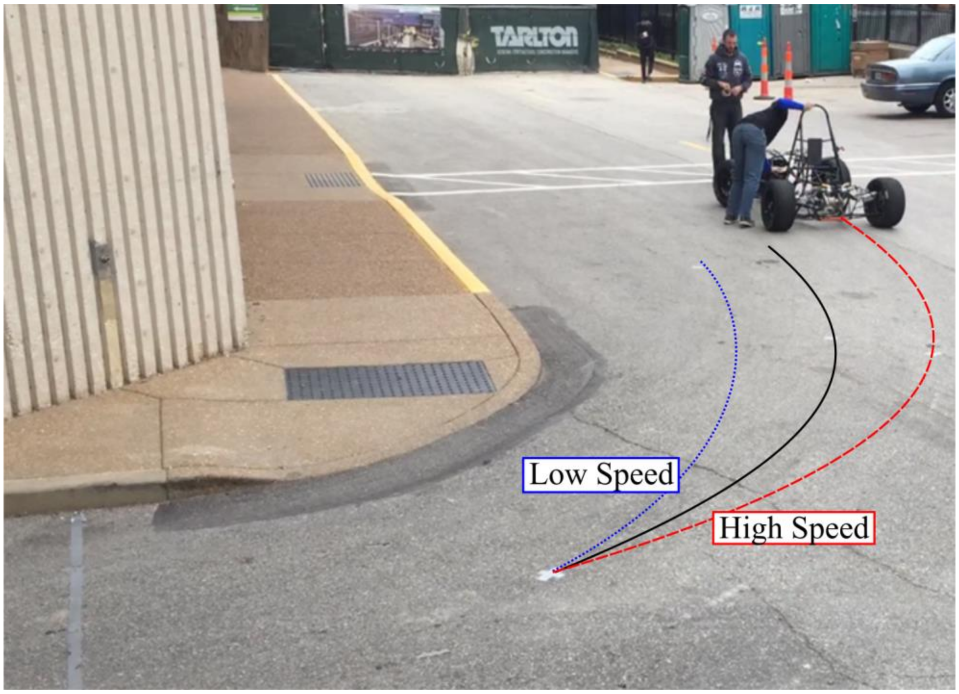

Figure 35 Turing Test with steering in high speed parallel steering setting, radius measured 24 ft. Lines approximate steering trajectories

7 DESIGN DOCUMENTATION

7.1 FINAL DRAWINGS AND DOCUMENTATION

7.1.1 Engineering Drawings

See Appendix C for select CAD models.

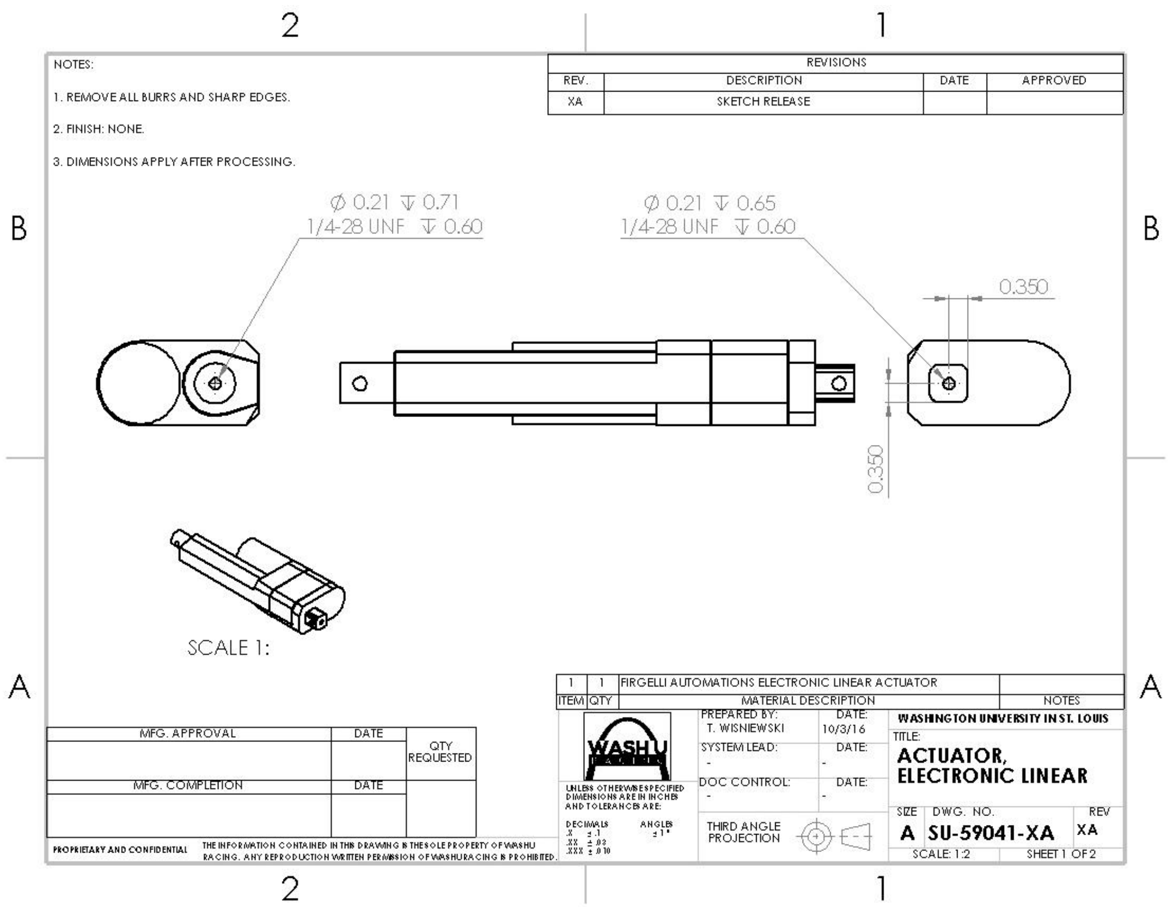

Figure 36 Drawing for electronic linear actuator modifications.

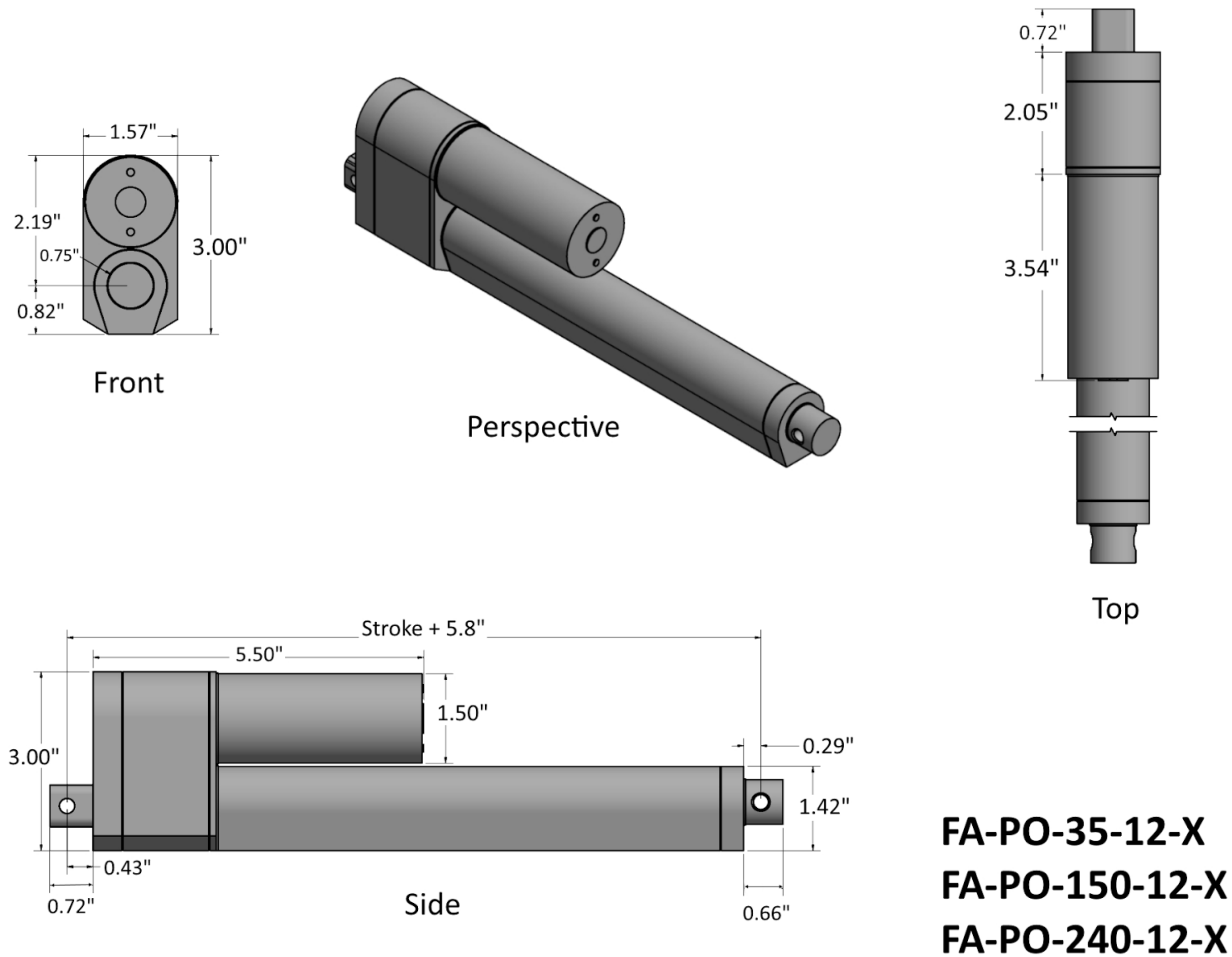

Figure 37 Technical drawing of linear actuators provided by Firgelli Automation (https://www.firgelliauto.com/products/feedback-rod-actuator).

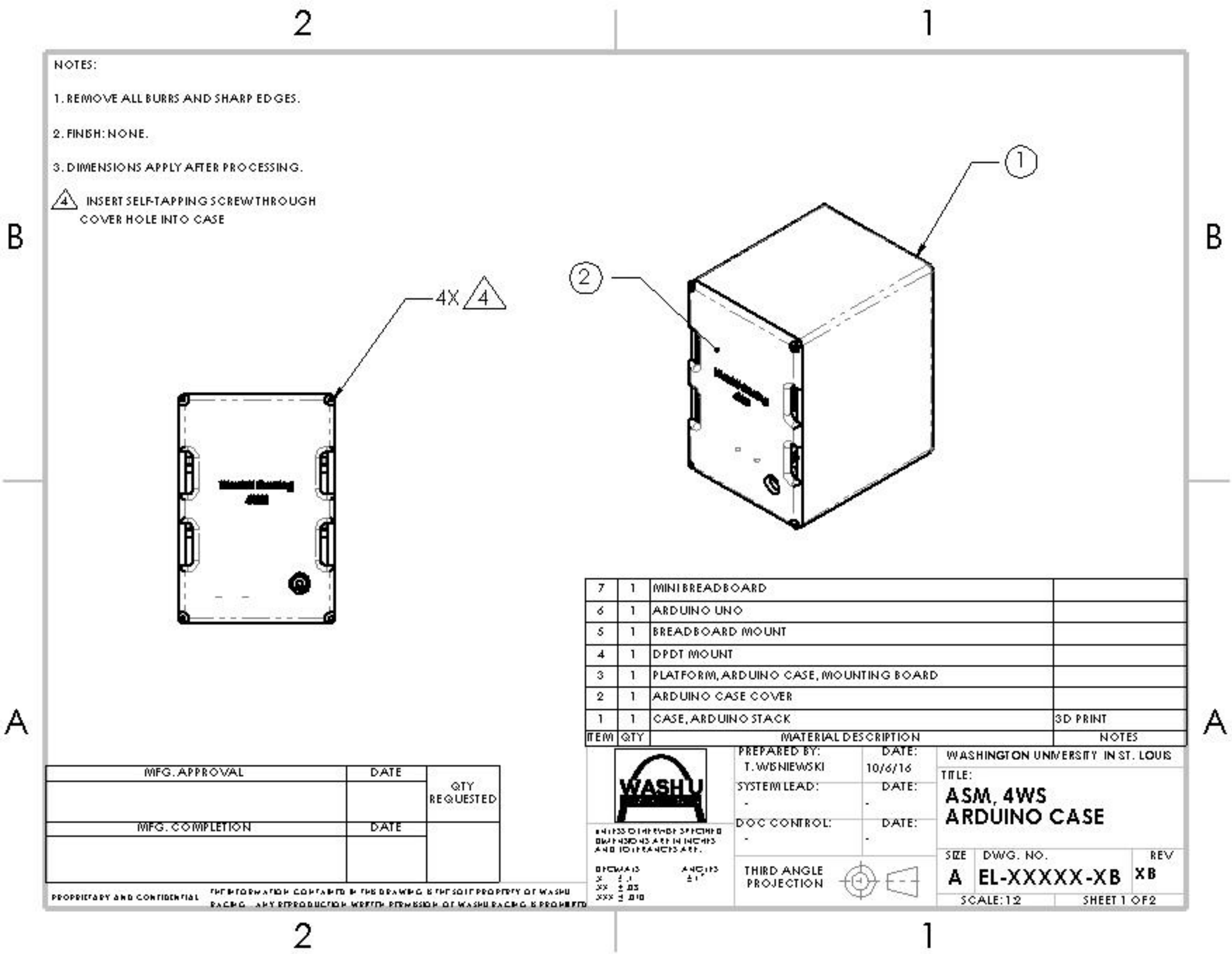

Figure 38 Assembly drawing for Arduino case (sheet 1).

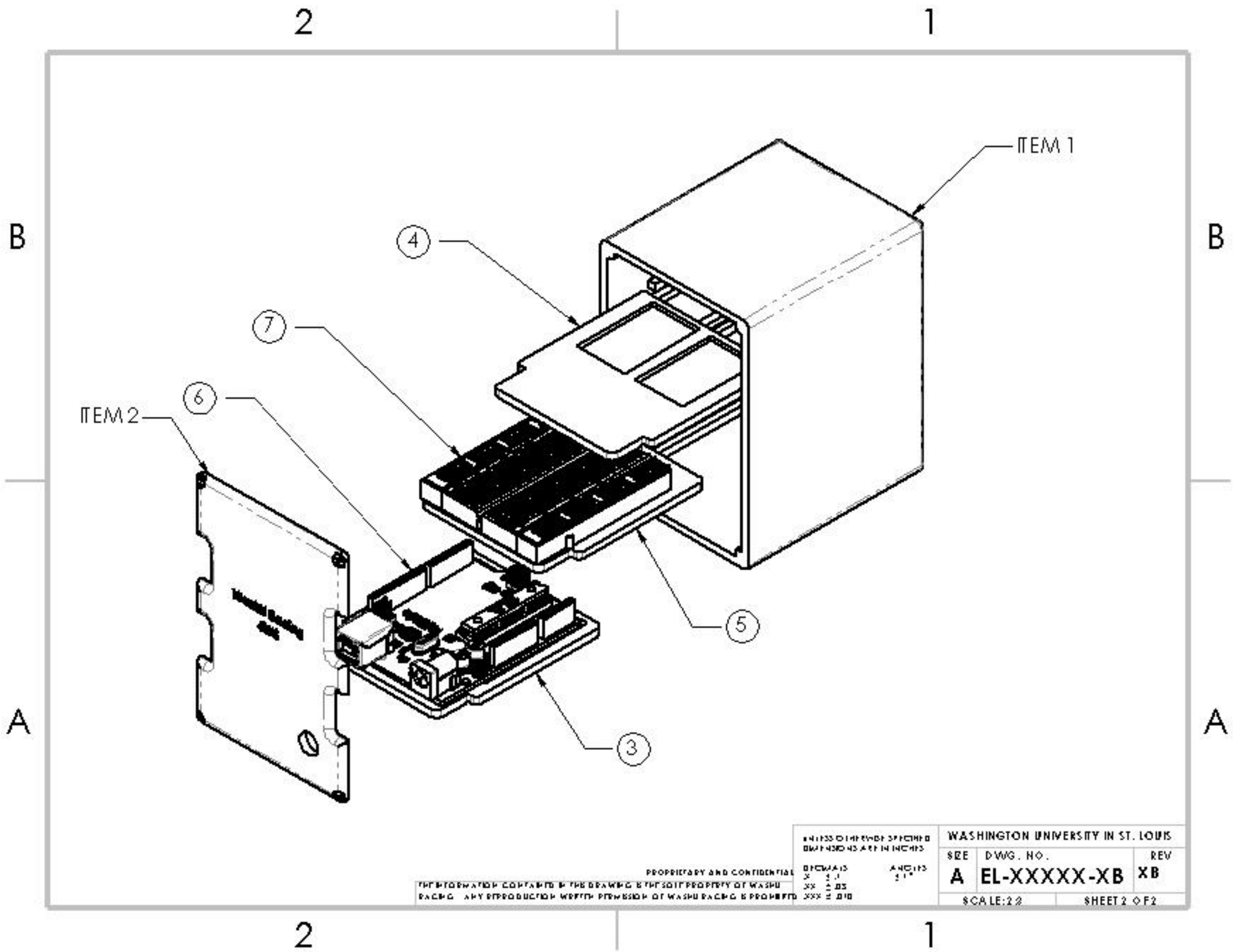

Figure 39 Assembly Drawing for Arduino case (sheet 2).

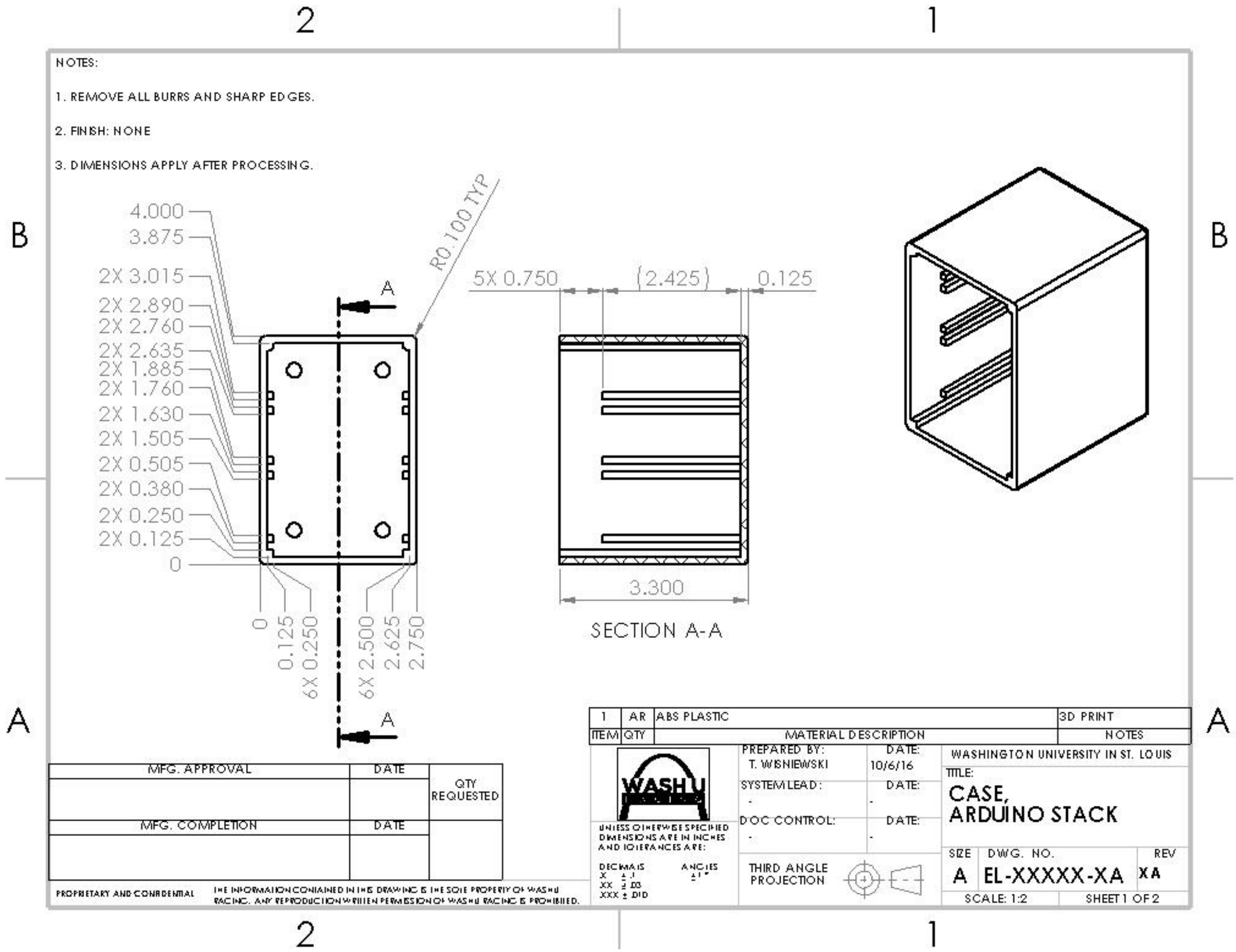

Figure 40 Arduino case part drawing.

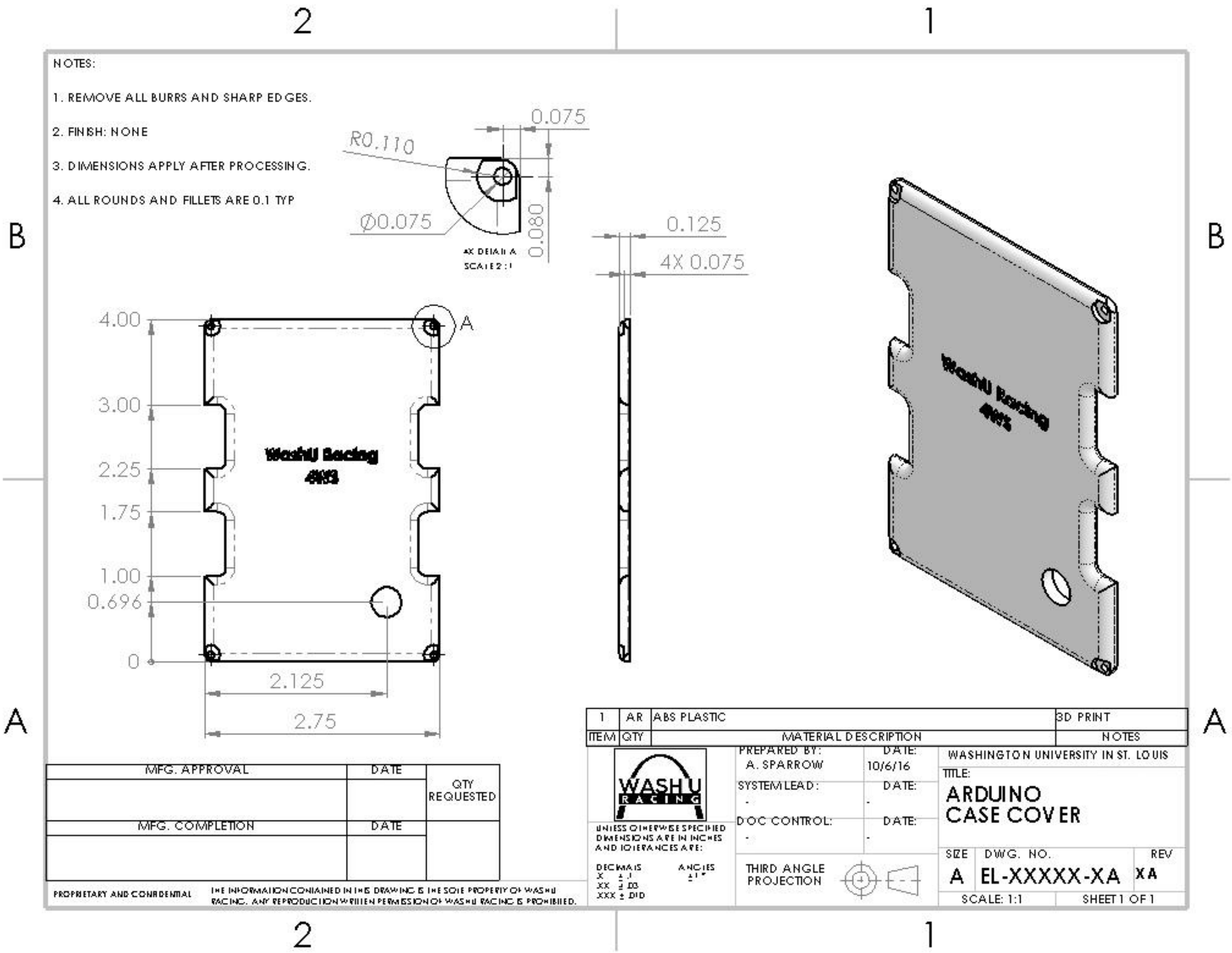

Figure 41 Arduino case cover.

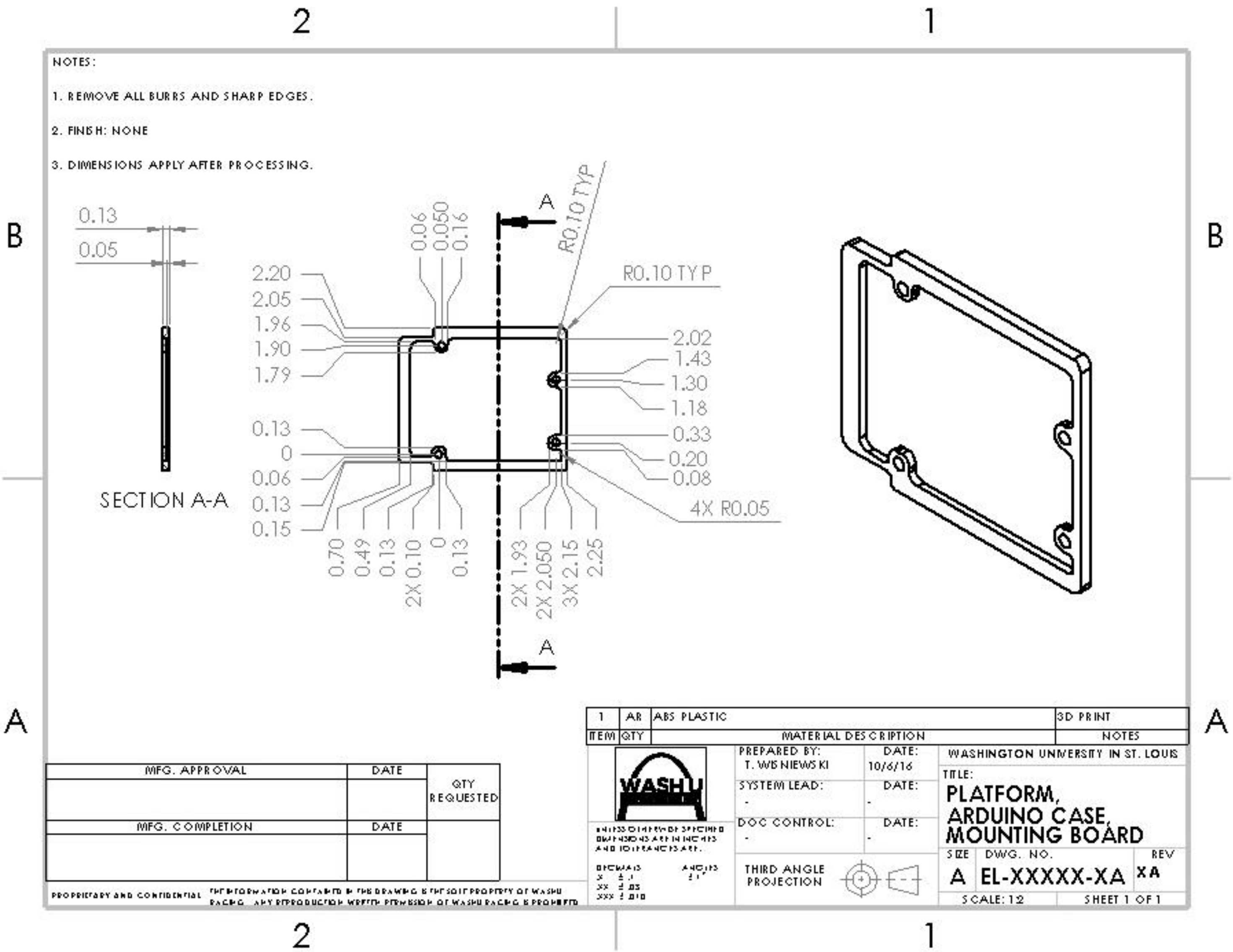

Figure 42 Arduino mounting board drawing.

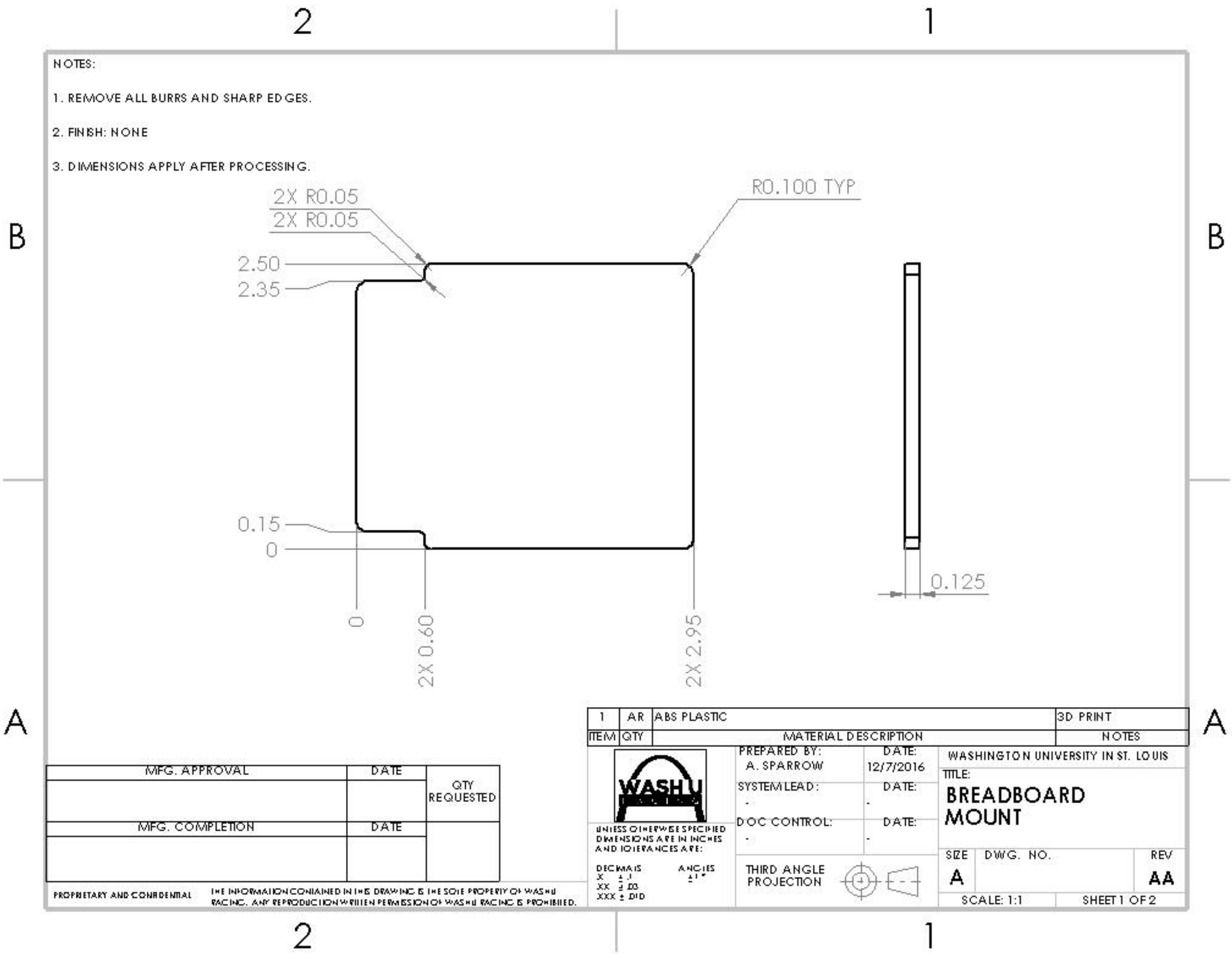

Figure 43 Breadboard mount drawing.

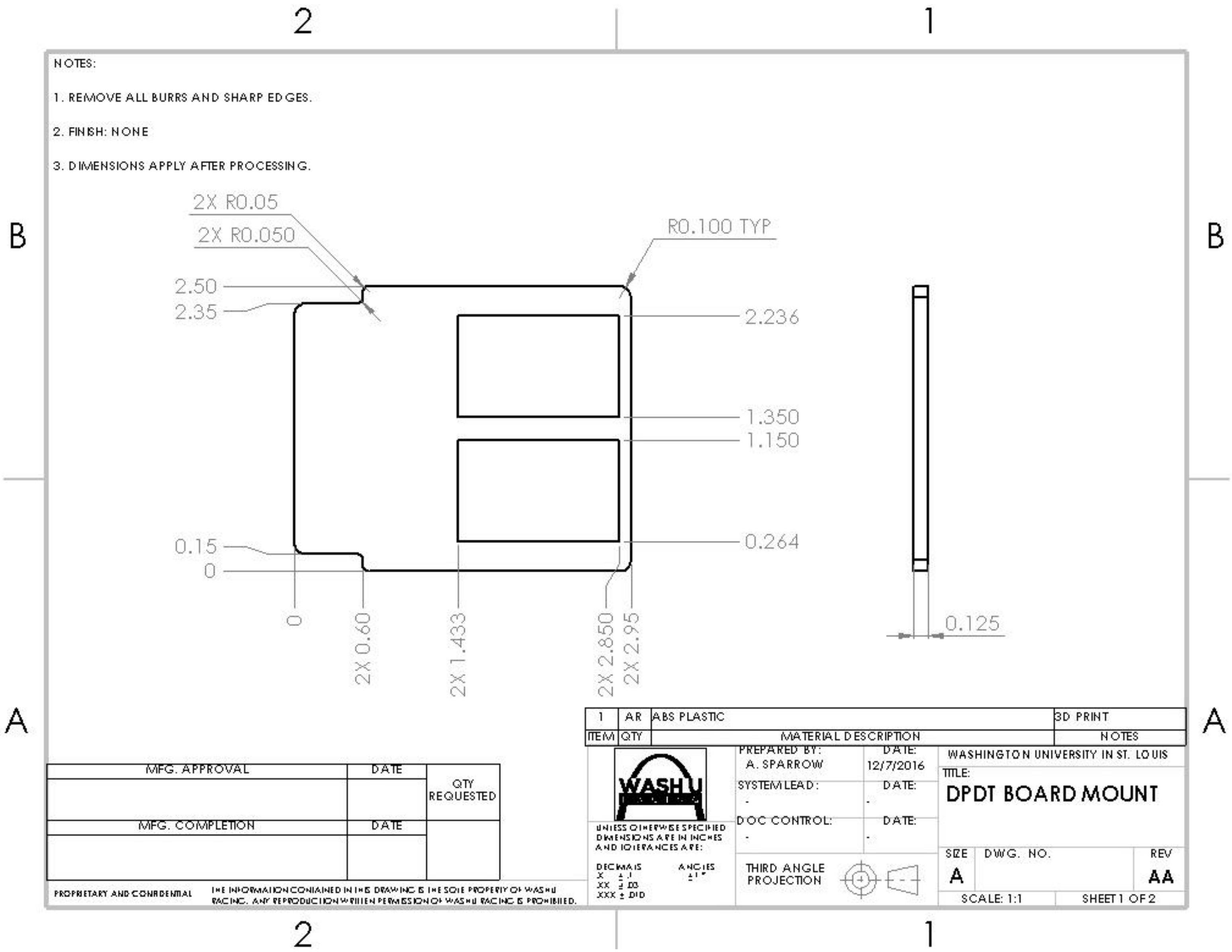

Figure 44 DPDT mount drawing.

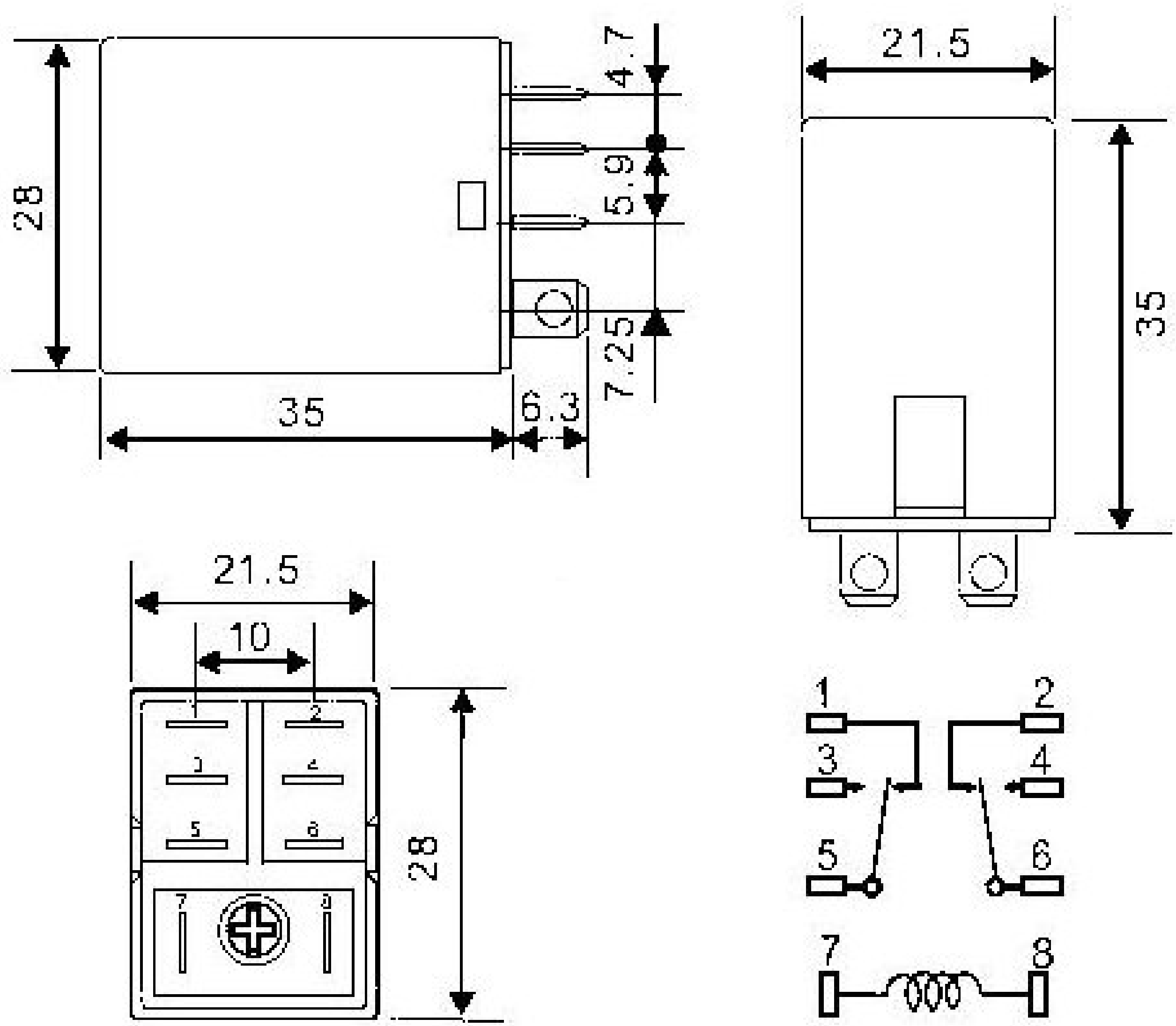

Figure 45 Technical drawing of double-pole double-throw switch provided by Firgelli Automation (https://www.firgelliauto.com/products/12-volt-double-pull-double-throw-relay).

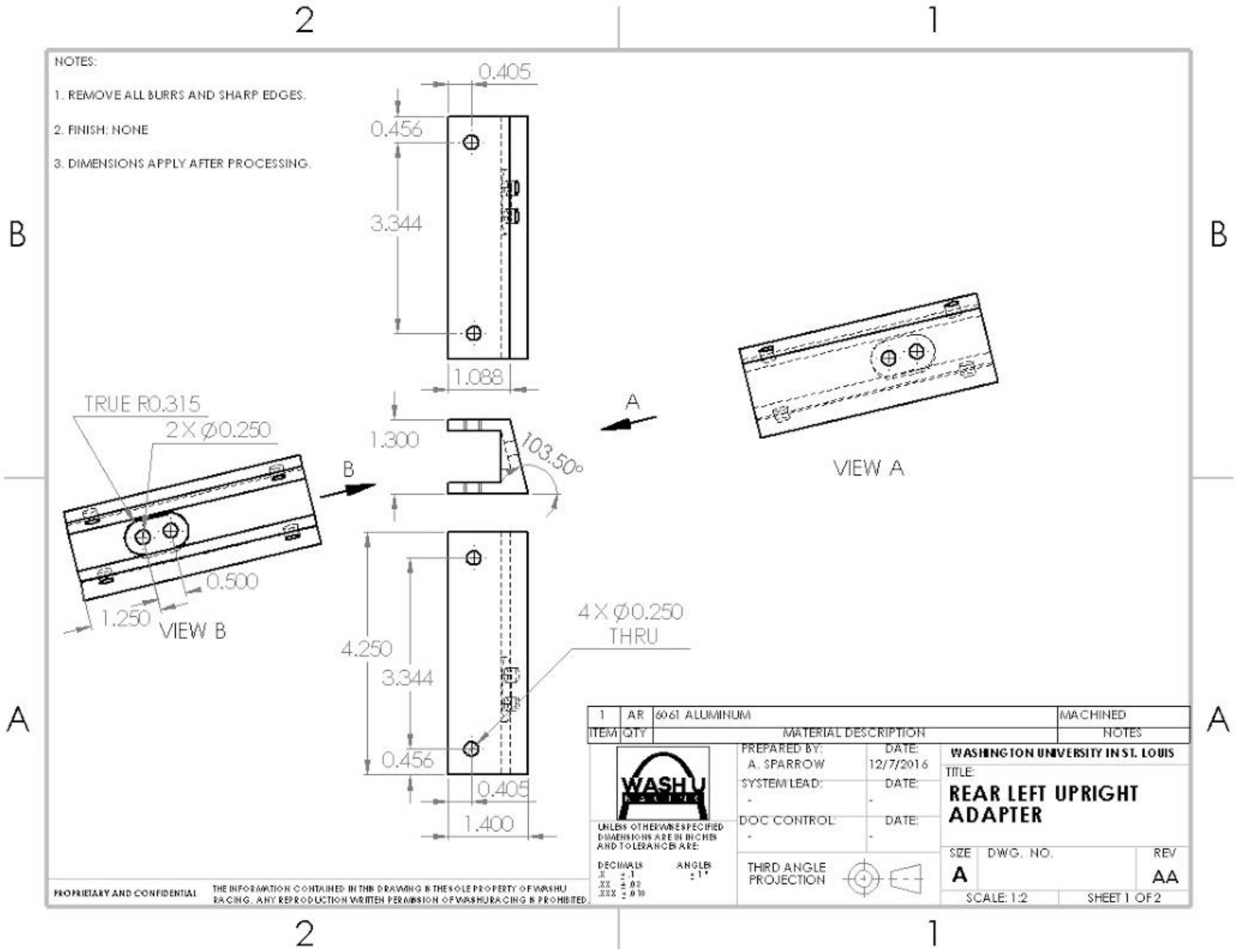

Figure 46 Rear left upright adapter drawing.

7.1.2 Sourcing instructions

- 2” Feedback Rod Linear Actuator
- 12V Battery
- 12V DPDT

7.2 FINAL PRESENTATION

7.2.1 A live presentation in front of the entire class and the instructors

This section is intentionally left blank.

7.2.2 A link to a video clip

Figure 47 Photo and link to a video presentation of the project https://youtu.be/sUXztFUZ-a8.

7.3 TEARDOWN

TEARDOWN TASKS AGREEMENT

PROJECT: I-4WS NAMES: Andrew Sparrow AS INSTRUCTOR: Dr. Mary Malast
Phil Russell PR
Theo Wisniewski TW

The following teardown/cleanup tasks will be performed:

After further discussion with Dr. Malast, we did not need to perform any tasks for we did not use any of the provided facilities. Project was completed in WashU Racing garage.

Instructor comments on completion of teardown/cleanup tasks:

Instructor signature: Mary Malast Print instructor name: Mary Malast
Date: 12/8/16

(Group members should initial near their name above.)

8 DISCUSSION

8.1 FINAL PROTOTYPE METRICS AND QUANTIFIED NEEDS

Table 9 Chosen concept design metrics revisited.

Metric Number	Metric	Units	Worst Value	Max Value	Actual Value	Normalized Value
1	Speed	in/sec	0	5	0.5	0.10
2	Weight	lb.	45	0	9.2	0.80
3	Cost	$	600	0	414	0.31
4	Packaging	Integer	10	0	1	0.90
5	Amount of Redesign	Integer	10	0	1	0.90
6	System Feedback	Integer	10	0	3	0.70
					TOTAL	**3.71**

In our original design metrics analysis, the electronic linear actuator without tie-rods concept scored a 4.136/6 based on the expectations of the final product. After the working prototype the same metrics again were analyzed. The prototype scored slightly lower according to the chosen metrics. The speed of the actuators met expectations, but the overall weight of the added system was slightly more than anticipated. The total weight was a function of the two actuators, battery, and electronics. Weight for the battery and electronics was underestimated in the original design, because the power requirements for the environment of use proved to be greater than anticipated. Cost was also higher than anticipated due to not accounting for additional circuitry for the electronic programming. Packaging and Amount of Redesign remained the same because all components fit as anticipated with no issues. While we used the position feedback from the actuators in the development of our program we expected error in the movement due to the lack of a control system being in place. There was not sufficient time to develop a control system to track the commands with zero error such as control for a ramp or step input. Moving forward a more accurate dynamics model would need to be developed in order to create a responsive and robust controller.

8.2 PART SOURCING ISSUES

There were no significant issues in part sourcing. All suppliers delivered purchases promptly. The primary issue with parts and timing was manufacturing existing parts for the car which had either failed or were lost in the disassembly process for the 2015 vehicle. Documentation on the existing parts were not functional nor existent for use. The WashU Racing team is currently undergoing changes to address this issue in the future.

8.3 DISCUSS THE OVERALL EXPERIENCE:

8.3.1 Was the project more of less difficult than you had expected?

The project was about as difficult as we expected. The mechanical design of the project was well within our developed skill set by being a part of the WashU Racing team. We also understood that the circuit design and programming were going to require the most amount of work because we are less experienced in that area.

8.3.2 Does your final project result align with the project description?

The project does align with the project description because active four-wheel steering was achieved. Ackerman steering was demonstrated at low speeds and parallel steering was demonstrated at high speeds.

8.3.3 Did your team function well as a group?

Our group worked well together throughout the duration of the project. Responsibilities were evenly distributed and every individual achieved their respective tasks accordingly.

8.3.4 Were your team member's skills complementary?

It was useful that each individual was an active member of the WashU Racing team and very knowledgeable about the various aspects of the race car. Putting each of our individual experiences and intelligence together really made this project possible.

8.3.5 Did your team share the workload equally?

Responsibilities were evenly distributed throughout the term as can be seen within the Gantt chart. Each individual successfully achieved their tasks given to them which contributed to the final success of the prototype.

8.3.6 Was any needed skill missing from the group?

The greatest skill missing with our group is extensive experience with complex programing. The most difficult and time consuming aspect of this project was the programing of the Arduino and the circuitry that helped control the actuators.

8.3.7 Did you have to consult with your customer during the process, or did you work to the original design brief?

The customer was not needed after their initial interviews for they laid out specific requests for the project. As a result, the group was able to follow the original design brief throughout the process.

8.3.8 Did the design brief (as provided by the customer) seem to change during the process?

The design brief provided by the customer did not change during the process.

8.3.9 Has the project enhanced your design skills?

The project significantly increased our individual experiences with programing. The majority of the group had little to no experience with the electronic aspects needed to successfully complete this project.

8.3.10 Would you now feel more comfortable accepting a design project assignment at a job?

The entire group feels comfortable accepting a design project assignment as a job. The race team is constantly going through this project on all systems of the car.

8.3.11 Are there projects that you would attempt now that you would not attempt before?

We would be willing to attempt projects that are beyond the standard bounds of our mechanical engineering degree. After this project working on interdisciplinary projects that require skills from several disciplines seems less intimidating and that we would be able to contribute to more aspects of such a project. Also

9 APPENDIX A - PARTS LIST

Table 10 Parts list.

Quantity	Part Name	Part Use
3	2" Stroke, 150lb Force Feedback Rod Linear Actuator	To extend and retract rear wheel toe angle
1	12V DC Battery	To power Linear Actuators
2	12 V DPDT	To electronically control the direction of the actuators
1	Arduino Uno	To program and control the system
1	Electrical Wires	To provide connections between Arduino, Battery, and Linear Actuators
1	Aluminum Stock for Adapters	To provide a connection to the Uprights for the Linear Actuators
4	1/4-28 Rod Ends with 1/4in spherical bearings	To connect the linear actuators to the frame and upright adapters
8	1/4-28 Grade 8 bolts	To fasten adapters to the upright and rod ends to the frame and adapters
1	2015 FSAE Car Frame and Suspension Assembly	Vehicle the four-wheel steering system is being applied to
2	Rotary Potentiometer	To measure steering wheel angle and provide input for wheel speed in static model
1	Arduino Stack	To house the electrical components
1	Arduino Stack Cover	To enclose the stack for the electrical components
1	Arduino Board Mount	A board mount to mount the Arduino Uno to inside the Stack
1	Breadboard Board Mount	A board mount to mount the Breadboard to inside the Stack
1	DPDT Board Mount	A board mount to mount the DPDT's to inside the stack

10 APPENDIX B - BILL OF MATERIALS

Table 11 Bill of Materials.

Quantity	Part Name	Price/Unit	Total Price
3	2" Stroke, 150lb Force Feedback Rod Linear Actuator	$ 139.99	$ 419.97
1	12V DC Battery	$ 45.00	$ 45.00
2	12 V DPDT	$ 11.00	$ 22.00
1	Arduino Uno	Supplied	$ -
1	Electrical Wires	Supplied	$ -
1	Aluminum Stock for Adapters	Supplied	$ -
1	FSAE Car Frame and Suspension Assembly	Supplied	$ -
4	1/4-28 Rod Ends with 1/4in spherical bearings	Supplied	$ -
8	1/4-28 Grade 8 bolts	Supplied	$ -
2	Rotary Potentiometer	Supplied	$ -
1	Arduino Case Assembly	3D Printed/ Supplied	$ -
		Total	$ 486.97

11 APPENDIX C - CAD MODELS

Selected CAD models can be found at the following link. Due to the fact that FSAE is a competition not all models are available.

https://drive.google.com/drive/folders/0B3neGL4GVVGLbk5VRWRYOUw4VlE?usp=sharing

12 APPENDIX D – ARDUINO CODE FOR CIRCUIT ANALYSIS

Below is the code used in the Autodesk Circuits analysis to prove the validity of the circuit design.

```
const int TActuatorL = 6;       // TActuatorR (Right Actuator) is the arduino connection from Digital 7 to
B of the Transistor connected to the DPDT relay (Determines extension or retraction of actuator)
const int OActuatorL = 7;       // OActuatorR (Right Actuator) is the arduino connection from Digital 8 to
B of the Transistor connected to the SPDT relay (Turns Motor on or off)
const int TActuatorR = 9;       // TActuatorR (Right Actuator) is the arduino connection from Digital 7 to
B of the Transistor connected to the DPDT relay (Determines extension or retraction of actuator)
const int OActuatorR = 8;       // OActuatorR (Right Actuator) is the arduino connection from Digital 8 to
B of the Transistor connected to the SPDT relay (Turns Motor on or off)
const int analogPin = A0;
int analogValue;                // Readings from Switch

void setup() {                  // Initalize pins used to control the motors as outputs
  pinMode(TActuatorL, OUTPUT);
  pinMode(OActuatorL, OUTPUT);
  pinMode(TActuatorR, OUTPUT);
  pinMode(OActuatorR, OUTPUT);
  pinMode(analogPin, INPUT);

  digitalWrite(OActuatorL, LOW); //Initializes Motor as Off
  digitalWrite(OActuatorR, LOW); //Initializes Motor as Off
  Serial.begin(9600);
}

void loop() {

extendRightActuator();
delay(2000); // Extends Right Actuator for 2 sec
stopRightActuator(); //Stops Right Actuator
extendLeftActuator();
delay(2000); //Extends Left Actuator for 2 sec
stopLeftActuator();
delay(2000); //Delays for 2 sec
retractRightActuator();
delay(2000); //Retracts Right Actuator for 2 sec
stopRightActuator(); //Stop Righst Actuator
retractLeftActuator();
delay(2000); //Retracts Left Actuator for 2 sec
stopLeftActuator(); //Stops Right Actuator
delay(2000); //Delays for 2 sec
retractRightActuator();
```

```
retractLeftActuator();
delay(2000); //Retracts Both Actuators for 2 sec
extendRightActuator();
extendLeftActuator();
delay(2000); //Extend Both Actuators for 2 sec
}
void moveActuator(int mot, int dir) { // A function to control actuators
  // mot == 0 is Left Linear Actuator, mot == 1 is Right Linear Actuator
  // dir == 0 is CCW, dir == 1 is CW

  boolean in1 = HIGH; // Default direction is CCW (Extend or Retract?)
  boolean in2 = LOW;

  if(dir == 1){ // Sets the dirction to CW (Extend or Retract?)
    in1 = LOW;
    in2 = HIGH;
  }
  if(mot == 0){ // if Left Actuator is specified adjust it's values
    digitalWrite(TActuatorL, in1);
    digitalWrite(OActuatorL, HIGH);
  }
  else{ // if the Left motor isn't selected adjust the Right Actuator
    digitalWrite(TActuatorR, in1);
    digitalWrite(OActuatorR, HIGH);
  }
}
void extendLeftActuator() { //Function extends the left actuator
  moveActuator(0,0);
}
void extendRightActuator() { //Function extends the right actuator
  moveActuator(1,0);
}
void retractLeftActuator() { //Function retracts the left actuator
  moveActuator(0,1);
}
void retractRightActuator() { //Function retracts the right actuator
  moveActuator(1,1);
}
void stopLeftActuator() { //Function stops the right actuator
 digitalWrite(OActuatorL, LOW);
}
void stopRightActuator() { //Function stops the right actuator
 digitalWrite(OActuatorR, LOW);
}
```

13 ANNOTATED BIBLIOGRAPHY

- SAE International, "FSAE Design Score Sheet," 2016. [Online]. Available: http://www.fsaeonline.com/content/FSAE%20Design%20Score%20Sheet%20150pt.pdf. [Accessed 25 April 2016].
    - The FSAE judges use a standard rubric when critiquing team's vehicles. The sheet is composed of each system of the car and contains detailed commentary to help critique the racecars.
- SAE International, "2015-16 Formula SAE Rules," 2015. [Online]. Available: http://www.fsaeonline.com/content/2016_FSAE_Rules.pdf. [Accessed 25 April 2016].
    - The FSAE competition has a strict set of rules, regulations, and guidelines to follow for competition. These rules are detailed within each system of the race car and must be followed to be allowed to partake at the annual competitions.
- R. N. Jazar, in *Vehicle Dynamics: Theory and Application*, New York, Springer Science, 2014, pp. 387-497.
    - Reza N. Jazar and colleagues provide detailed text about the various dynamics behind vehicles. Theory is applied in real world applications to help make connections for the reader.
- J. Allwright, "Four Wheel Steering (4WS) on a Formula Student Racing Car," *SAE-A*, vol. 1, no. 1, 2015.
    - Joshua Allwright writes a detailed journal about the various benefits four-wheel steering provides for FSAE racecars. Results include theoretical calculations in performance increases for most dynamic events within the FSAE competition.
- SAE International, "FSAE Michigan 2015 Results," 2015. [Online]. Available: http://students.sae.org/cds/formulaseries/results/fsae_mi_2015_result.pdf. [Accessed 24 April 2016].
    - FSAE Michigan is a competition for colleges across the world to come and compete with their racecars. FSAE posts the results for the events once the competition is over so teams can view for later use.
- Severson, "Four-Wheel Steering Demystified," Autoweek, 12 June 2015. [Online]. Available: http://autoweek.com/article/car-life/four-wheel-steering-demystified. [Accessed 25 April 2016].
    - From the Honda Prelude to today's Porsche 911, four-wheel steering has been an emerging technology for quite some time. *Autoweek* outlines the technology and how it has advanced into modern times for commercial vehicles.
- Porsche, "Press Information: Porsche 911 and 911 Turbo S," 7 2013. [Online]. Available: http://press.porsche.com/vehicles/2014/PM_911_Turbo_Coupe_USA.pdf. [Accessed 25 April 2016].

- When announcing the new 911 Turbo Coupe, Porsche joined in on the four-wheel steering revolution by implementing it on their sports car. Their detailed press release goes deeper into their plan for production of the vehicle and what to further expect.